# KANSAS GEOLOGICAL SURVEY
# OPEN-FILE REPORT 93-28

## A MODEL OF MISSOURIAN OOLITIC PETROLEUM RESERVOIRS BASED ON THE DRUM LIMESTONE IN SOUTHEASTERN KANSAS

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# INTRODUCTION

This report contains results of the Drum Limestone subtask portion of a three-year study on "Depositional sequence analysis and sedimentologic modeling for improved prediction of Pennsylvanian reservoirs" that was funded by the Department of Energy. The Drum Limestone was investigated as a potential surface analog for oolitic reservoirs in the Lansing Kansas-City Groups in central and western Kansas. The study area in Montgomery County, Kansas was chosen because the Drum Limestone contains a well-developed oolite that can be studied in outcrops and well-logs, and because a complete depositional shelf to basin transect can be observed along the outcrop belt. Major controls on oolite deposition appear to include pre-Drum depositional topography, sea-level history, shelf margin currents, and possibly local structural elements. Pre-Drum topography was controlled by thickness changes in underlying units and possible tectonic movements. In the oolite facies, the Drum has high porosity and low permeability similar to many Lansing-Kansas City Group reservoirs and apparently has an overall similar diagenetic history with the reservoirs.

The Drum Limestone is part of the Missourian (Upper Pennsylvanian) Kansas City Group (Fig. 2.A.2.1) which is characterized by alternating limestones, many of which are oolitic, and siliciclastic units. During Kansas City Group deposition, eastern Kansas was the site of shallow water to terrestrial settings on a tectonically stable shelf. Siliciclastic wedges prograded to the south and southwest from Missouri. The Anadarko and Arkoma basins in southern Kansas, Oklahoma, and Arkansas were rapidly subsiding and dominated by siliciclastic deposition. Major siliciclastic wedges prograded from the south keeping pace with subduction and spilling over to the carbonate shelf in Kansas. The study area is near the southern limit of carbonate deposition at the broad boundary between the slowly subsiding shelf to the north and the more rapidly subsiding basin to the south.

The primary goals of this project were to develop a predictive model of oolite accumulation and porosity development applicable to Lansing-Kansas City Group oolitic petroleum reservoirs by studying the outcrops and shallow subsurface of the Drum Limestone in Montgomery County. Subtasks within the Drum Limestone outcrop analog were to determine the sedimentologic and general diagenetic history of the Drum oolite body, to determine the relationship between facies and geometry of the Drum Limestone and facies and geometry of underlying and overlying units, and to determine the possible role of tectonism and sea-level fluctuations as controlling factors in depositional history of the Drum Limestone and associated strata. Also investigated were possible causes of reservoir heterogeneities that would affect fluid flow within the porous zones of the oolite.

## METHODOLOGY

The initial phase of this study was mapping of the Drum Limestone. The Drum Limestone was mapped along the outcrop belt from northernmost Montgomery County southward to the edge of the oolite (Appendix I). In the subsurface the Drum Limestone and related units were mapped with geophysical logs from oil wells. This mapping extended from Township 30 S southward to the Kansas border, and from Range 13 E eastward to the outcrop belt (Range 16 and 17 E). Mapping data was supplemented with 9 cores. Seven cores were taken along a depositional shelf-to-basin transect southwest of Independence. Two cores were taken along the outcrop belt. Gamma ray-neutron logs were acquired for all cores. Three high-resolution seismic lines were acquired southeast of Independence along the coring transect. These data provided additional information on the geometry of the Drum Limestone and related units. Petrographic data were obtained from thin sections taken from outcrop and core samples.

## OUTLINE OF MAJOR STRATIGRAPHIC UNITS

The study interval in Montgomery County represents a departure from the more typical expression of Missourian cyclothems (sensu Heckel, 1977). The Drum Limestone can be traced from northeastern Kansas (where it is generally correlated with the Westerville Limestone) to southeastern Kansas where it pinches-out. The Drum limestone is characteristic of many regressive limestones of Heckel (1977) in that it is laterally continuous, thick, contains oolites, and has evidence of exposure. Yet in the study area the Drum Limestone is different from classic regressive limestones in that it is not associated with a core shale, and it is overlain and underlain by siliciclastic facies instead of shale facies that are normally characteristic of "outside" shales.

The stratigraphic units focused on in this study extend from the Mound Valley Limestone to the sandstones and shales of uncertain affinity immediately above the Drum Limestone. The Mound Valley Limestone is generally a wackestone to packstone that is thickest in the northern part of the study area (up to 25 ft thick [7.6 m]) and gradually thins southward to a pinch-out (Fig. 2.A.2.2). The overlying Galesburg Shale consists of sandstone, shale, and coal. The source of this sediment is from the south (Stermer, 1992) and the Galesburg thickens dramatically southward to approximately 150 ft (45.7 m) (Fig. 2.A.2.3). However, unlike underlying units, the Galesburg does not thicken gradually but has a complex pattern of thick and thin areas. The cause of this is not clear, but some of the thick and thin patterns are parallel to northeast- and northwest-trending basement structures. This may suggest that Galesburg deposition was responding to basement faults.

The Dennis Limestone, overlying the Galesburg Shale, from base to top consists of the thin (generally under 5 ft [1.5 m]) transgressive Canville Limestone (Fig. 2.A.2.4), the Stark Shale, a fissile black, platy shale, and the thick, regressive Winterset Limestone (Fig. 2.A.2.5). During Winterset deposition a shelf edge was established in southern Wilson County, a few miles north of the Montgomery County border. The Winterset Limestone thins from nearly 100 ft (30.5 m) thick in central Wilson County to under 10 to 15 ft (1.5 m) in central Montgomery County.

The Cherryvale Shale, overlies the Winterset Limestone, and apparently filled in topographic low areas left after Winterset deposition, and extended the depositional shelf edge further to the south (Fig. 2.A.2.6). The general morphology of the Cherryvale Shale in the study area suggests a primary delta lobe that was prograding to the southwest from eastern Montgomery County, and a minor lobe in west-central Montgomery County. The Cherryvale consist of unfossiliferous, grey shale with siderite bands and concretions, and does not contain a succession of facies characteristic of deltas, therefore it is difficult to interpret the exact environment of deposition for the Cherryvale Shale.

The Drum Limestone overlies the Cherryvale Shale. The thickness and facies patterns of the

Drum Limestone were apparently responding to depositional topography left after Cherryvale Shale deposition stopped (Fig. 2.A.2.7). This topography resulted in a relatively flat depositional shelf in central and northern Montgomery County where the Drum is generally thin. A depositional shelf edge was created at the southern edge of the Cherryvale Shale. The Drum Limestone thickens dramatically south of the shelf edge, and then thins basinward.

## DRUM LIMESTONE FACIES DESCRIPTIONS

Interbedded limestone and shale facies: The lower part of the Drum Limestone in most places along the outcrop belt in the study area consists of alternating beds of limestone and shale. Limestone beds range from 1 to 7 inches (3 to 17 cm) thick (Fig. 2.A.2.8, 9). Where this facies is thickest in southern Montgomery County, the shale interbeds gradually thicken downwards through the facies from thin (approximately 0.1 inch or 2.5 mm) clay drapes near the top to over 5 inches (25 cm) thick near the base. Upper and lower boundaries of beds appear gradational. Average thickness of shale beds near the middle of the facies is 4 inches (12 cm). Most limestone beds are composed of laminated mudstone. Laminations are distinct on weathered surfaces, but, in thin section are indistinct, rarely observable as slight changes in crystal size, or are represented by laminae of quartz silt. In addition to the common irregularly spaced, horizontal laminations, there are small ( 1 inch or 2.5 cm long) cut and fill structures as well as rare, possible ripples. In the southern portion of the study area bioturbation increases upwards: laminations become more disturbed by burrows, mudstone-filled burrows extend down into shale interbeds, and pellets become more abundant. Some beds are composed of peloidal packstone to grainstone. Cross beds up to 10 inches (25 cm) thick are also present. Rare tabulate corals are the only fossils that have been observed in this facies.

Intraclastic grainstone to packstone facies: This facies consists of flat pebbles composed of medium-crystalline spar (probably neomorphosed mudstone) and shale clasts rich in quartz silt. Pebbles range in length up to 1.2 inches (31 mm) long and are up to 0.2 inches (5 mm) thick. Most pebbles are 0.2 to 0.4 inches (5 to 10 mm) long and 0.08 to 0.1 inches (2 to 3 mm) thick. Fossils within this facies include brachiopods, bivalves, gastropods, bryozoans, and echinoderms. Most fossils are broken and abraded. Other allochems include oolites, coated grains, and peloids. Many of the pebbles have oolitic coatings as well. North of the Heartland Cement Quarry this facies consistently occurs as a thin bed generally 2 to 3 inches (5 to 7.5 cm) thick, but ranging up to 9.5 inches (24 cm thick) at the base of the interbedded limestone and shale facies and apparently forms a continuous bed at the base of the Drum Limestone (Fig. 2.A.2.7-B). This particular bed is rarely cross-bedded and is distinguished from other occurrences of the facies because it contains foraminifers encrusting the pebbles. At one outcrop where the contact between the Drum Limestone and underlying Cherryvale Shale can be traced for several meters, the bed of intraclastic grainstone to packstone rests unconformably on the Cherryvale. At the Heartland Cement Quarry and in the White #1, core the interbedded limestone and shale facies grades downward into the Cherryvale Shale, and a bed of the intraclastic grainstone to packstone facies (with encrusting foraminifers) occurs in the middle of the interbedded limestone and shale facies. The intraclastic grainstone to packstone facies occurs sporadically at the base of the bryozoan, stromatolitic wackestone to boundstone facies and skeletal, oolite grainstone facies as well.

Bryozoan, stromatolitic wackestone to boundstone facies: This facies consists of fossiliferous wackestone with an abundant and diverse fossil assemblage consisting of large fenestrate bryozoans, encrusting bryozoans, brachiopods, crinoid plates, and gastropods. Some of the fenestrate bryozoan colonies are complete and are over 20 cm long. The bryozoan stromatolitic wackestone to boundstone facies thickens gradually from 2 ft (0.6 m) in northern Montgomery County to 4 ft (1.2 m) east of Independence, and then thins to a feather edge near Independence. This facies is absent in the Heartland Cement Quarry. In the northern-most outcrops in Montgomery County this facies contains well-developed, steep-sided, elongate stromatolites (Fig. 2.A.2.10). Based on observations from overturned blocks, the stromatolites are arranged in parallel rows, and aligned asymmetrically in one direction, suggesting deposition in response to waves or currents probably in very shallow water. Near the southern terminus of the bryozoan stromatolitic wackestone to boundstone facies there are boundstone mounds constructed of stromatolites and encrusting fistuliporoid bryozoans. Oncolites that nucleated on fossil debris are common in some exposures, suggesting high energy conditions. Ooids are a rare component of this facies.

Skeletal oolitic grainstone facies: The skeletal oolitic grainstone facies is thickest immediately south and southwest of the edge of the Cherryvale clastic wedge. The facies is best exposed in the Heartland Cement Quarry where it is approximately 50 ft (15.2 m) thick (Fig. 2.A.2.11). Petrographic observations reveal that the composition ranges from nearly pure, well-sorted oolite, to poorly sorted oolitic fossiliferous grainstone and a small amount of packstone. Fossils are abundant and diverse, including fenestrate bryozoans, echinoderm ossicles, brachiopods, ramose bryozoans, gastropods, bivalves, rugose corals, tabulate corals, and cephalopods.

The main body of the oolite is well exposed in the mile-long (1.6 km) highwall of the Heartland Cement quarry and consists of thick (3 to 4 ft, 1 to 1.3 m) tabular, planar cross beds at the base of the oolite and grade upwards to thinner, trough cross beds at the top. Current orientations are predominantly to the southwest with a minor mode to the northeast (Hamblin, 1969) (Fig. 2.A.2.12). There is also an increase in shale content upward in the uppermost 10 ft (3.05 m) of the Drum Limestone in the quarry. Troughs are separated by shale drapes, that grade upward into isolated troughs surrounded by shale.

Northward the skeletal oolite grainstone facies is thin (generally under 20 ft [6.1 m]) on the Cherryvale shelf where the oolite overlies the bryozoan stromatolitic wackestone to boundstone facies. The contact between the two facies in that area is sharp and erosional. In most outcrops there is clear evidence of erosion of the bryozoan stromatolitic wackestone to boundstone facies after lithification. In one exposure (Lib-5, see Appendix I) it appears that paleosol features developed on the bryozoan stromatolitic wackestone to boundstone facies and were later buried by the skeletal oolite grainstone facies. The skeletal oolite grainstone facies thins northward to a pinch-out.

South of Independence the skeletal oolite grainstone facies rests on the interbedded shale and limestone facies. The skeletal oolite grainstone facies thins southward to a pinch-out approximately 4 miles south of Independence along the outcrop belt. In the subsurface this facies pinches out within a mile of the edge of the Cherryvale shelf.

## DEPOSITIONAL ENVIRONMENTS AND SEA LEVEL HISTORY

The wide range of lithofacies and thicknesses of the units considered in this study indicate that there was significant sea floor topography prior to Drum Limestone deposition. The lowest unit studied, the Mound Valley Limestone which generally thickens northward. This is followed by the Galesburg Shale that is thickest in the southern part of the study area, but otherwise displays a complex series of thick lobes of shale. The origins of these features are not clear, however there is no obvious pre-Galesburg incisement, and this unit probably represents deltaic or fluvial deposition (Stermer, 1992). One notable pattern is the tendency for thick and thin zones of Galesburg to be northeast trending, and parallel to basement structural trends in this area. The overlying Dennis Limestone also shows a pronounced northeast-trending pattern of isopach lines, but there is no clear relationship between the thickness of Dennis Limestone and Galesburg Shale, however, the there is a thin area of Galesburg Shale directly below the thickest Drum Limestone in the area of the seismic lines and coring transects (Fig. 2.A.2.13, 14, 15).

The overlying Cherryvale Shale forms a delta lobe that prograded to the south and west (Fig. 2.A.2.14). The Cherryvale Shale apparently filled in a low area just south of the Dennis buildup and extended the depositional shelf edge further southward (Fig. 2.A.2.15). Thus, the northern edge of the Cherryvale Shale lobe does not represent a depositional shelf edge; only the western and southern edges likely represent delta shelf edges. The contact between the Cherryvale Shale and Drum Limestone is exposed at several locations, but only at Lib-5, where it be traced for several 10's of ft, is the erosional nature of the contact be exposed (Fig. 2.A.2.8-B). The origin of this contact remains enigmatic; there is little relief associated with the surface on the Cherryvale lobe based on subsurface analysis, and no evidence of subaerial exposure has been observed. The contact may represent a ravinement surface. North of the quarry this surface is overlain by an apparently deepening upward sequence of facies starting with an intraclastic fossiliferous limestone. This limestone may represent deposition during transgression. Local scouring and/or channeling in lower Drum beds suggests relatively shallow-marine conditions. Above the lowest limestone bed in the Drum is the interbedded limestone and shale facies. The paucity of bioturbation, fossils, and current structures all suggest a relatively deeper, quiet-water marine environment. Basinward (to the south) the interbedded limestone and shale facies thickens, and rests conformably on the Cherryvale Shale. Near the center of the facies is an intraclastic grainstone with abundant foraminifers. This bed may be the basinward extensions of the lowest limestone in the shelf position. Thus, the erosional surface on the Cherryvale shelf may be represented by continuous deposition in the basin.

On the shelf, the bryozoan stromatolitic wackestone to boundstone facies overlies the interbedded limestone and shale facies. The predominance of stromatolites, abundant and diverse fossils, and general low energy conditions, all suggest shallow-water, protected lagoonal deposits. The upper contact of the bryozoan stromatolitic wackestone to boundstone facies is sharp and was eroded after lithification. Features such as autobrecciation, laminated crusts, iron staining and circumgranular cracking at LIB-4 suggest subaerial exposure, and thus the bryozoan, stromatolitic wackestone to boundstone facies represents a shallowing upward trend capped at least locally by a probable subaerial exposure surface. However, it is not known yet if this exposure surface represents a relative drop in sea level or was caused by autogenic processes.

Overlying the erosional and possible subaerial exposure surface is cross bedded oolite deposited upon transgression of the sea over the previously exposed shelf and renewed shallow-water marine deposition. The oolite is thin over the shelf probably in response to limited accommodation space. As the Cherryvale thins to the south and west, the oolite thickens up to 65 ft (19.8 m). The ooids were probably being generated at the break in slope and transported seaward by tidal currents. Upward thinning of cross-bed units may suggest shallowing and filling of accommodation space. Carbonate deposition was halted by renewed influx of siliciclastic detritus.

# HIGH RESOLUTION SEISMIC STRATIGRAPHY

## Introduction

A high-resolution seismic-reflection study was conducted in the Drum Limestone study area in an effort to image geometric changes within Missourian stage strata at depths of up to 350 ft (106.7 m). These features are significant from both a geologic and geophysical perspective. Three seismic lines were acquired. Line 1 is a transect across the center of the thickest oolite, from a thin shelf limestone to the north, to the limestone pinch-out to the south over a distance of 1 mile (Fig. 2.A.2.19). A coring transect and well-log control were used to model the line prior to data acquisition. Lines 2 and 3 are also transects across the shelf edge, but in a position where the oolite is not well developed (Fig. 2.A.2.19). The geometry of the Drum Limestone was not know in the area of line 2 prior to data acquisition. Line 2 is at the southern end of this line and was intended to image the dramatic thickness changes in the Galesburg Shale through Drum Limestone.

This study highlights the geophysical aspects of quantifying practical thin-bed resolution. The data were acquired and processed to focus on a distinct shallow high-resolution seismic reflection at approximately 65 ms within the Galesburg Shale where the shale thins from 63 ft (19 m) to 23 ft (7 m).

The thin-bed resolving power of the CDP seismic-reflection technique is dependent upon the dominant frequency of the recorded reflection wavelet (Widess, 1973). Increasing the dominant frequency of recorded reflection signal involves: (1) generating a high-frequency source pulse, (2) sensing the signal with receivers with high voltage output, low noise, and a flat frequency response over the desired high frequencies, (3) recording the signal digitally on a seismograph with a large instantaneous dynamic range and electronically quiet analog filter and gain capabilities, and (4) optimizing the spread interval and receiver spacing for the target of interest (Knapp and Steeples, 1986). Criteria for resolving converging thin-bed sequences relies on observations of interference as evidenced by distortion of reflection waveforms (Ricker, 1953).

Practical resolution limits are dependent not only on recorded reflection frequencies but also on wavelet characteristics and noise. Zero phase wavelets possess the highest resolving potential (Knapp, 1990). A known theoretical wavelet can be phase-filtered to zero phase. Successful application of deconvolution requires a statistically large number of unique reflection wavelets and data with a large signal-to-noise ratio (Yilmaz, 1987). Shallow high-resolution reflection data sets rarely have more than four to six reflections and are notoriously noisy (Steeples and Miller, 1990). Practical optimization of shallow high-resolution data sets by phase filtering to zero phase is generally not possible.

## Field Procedures

The selected low-cut filters have a 18 dB/octave rolloff from their indicated -3 dB point. Production lines were acquired with 100 Hz analog low-cut and 500 Hz analog high-cut filters. The 1024 samples recorded per trace were at a 1/2 ms sampling interval. The dynamic range of the seismograph was more than adequate to record high-quality reflection information in the presence of source-generated and cultural noise at this site.

A series of walkaway-noise tests was conducted prior to acquisition of the production seismic lines. The spectral and total energy characteristics of the downhole .50-cal. seismic source made it the source of choice at this site for this geologic target. The receiver array consisted of three 40-Hz geophones equally spaced over approximately 3 ft (0.9 m) and centered on each station. The receiver array was designed in an attempt to attenuate some of the source-generated noise (Steeples and Miller, 1990). Analysis of the noise tests allows acquisition parameters and equipment to be optimized for the site conditions.

The nominal 12-fold CDP production line (line 2) and 24-fold CDP production lines (lines 1 & 3) were acquired using an end-on source/receiver geometry. Analysis of the walkaway data allowed determination of an optimum source-to-nearest-receiver offset of 55.8 ft (17 m) and source-to-farthest-receiver offset of 246 ft (75 m). A large component of direct and refracted wave energy inhibited closer source-to-receiver offsets. Near vertically incident recording minimizes normal move-out corrections and the associated stretch allowing a higher frequency, less distorted reflection wavelet to be recorded (Miller et al. 1990). The target reflector for line 2 is approximately 246.1 ft (75

m) deep which is within the optimum recording offset as evidenced by the walkaway-noise tests and general rules of thumb (Knapp and Steeples, 1986).

## Data Processing

The CDP data were processed at the Kansas Geological Survey (KGS) using a proprietary set of algorithms developed by the KGS (Eavesdropper). Extreme care was used during the editing process to ensure removal of all non-seismic energy that could either be misinterpreted as reflections on stacked data or that hampered interpretations of real reflection events. Velocity analysis incorporated iterative constant velocity stacking with detailed 1/5 wavelength surface-consistent statics to improve both accuracy of velocity corrections and time/depth conversion on interpreted cross sections. The main distinctions between the shallow high-resolution processing flow used on this data and most routine petroleum sequences relate to conservative use and application of correlation statics, precision required during velocity and spectral analysis, extra care during muting operations, and lack of deconvolution.

## Modeling and Interpretation

As an aid to the interpretation of the seismic lines geologic cross-sections (Figs. 2.A.2.18, 19), corresponding two-dimensional geologic models and synthetic seismograms were generated for lines 1 and 2 (Figs. 2.A.2.20, 21). The geologic cross-sections are structurally consistent with well control from the Clarkson #2 core (Fig. 2.A.2.19) at trace 494 on line 2 (Fig. 2.A.2.22). The velocities and densities incorporated into the models are consistent with the lithologies encountered in the Clarkson core, check shot survey data at the same well site, and stacking velocity control. The cross-sections in Figs. 2.A.2.20 and 21 are presented as reasonable representations of that portion of the subsurface imaged by the seismic control and illustrate some of the geometric details which characterize the Missourian stage strata in the study area.

The two-dimensional synthetic seismograms (Figs. 2.A.2.20, 21) were generated for the geologic models using Geophysical Micro-Computer Ltd. diffraction modeling software. A 5 ms, zero-phase, normal-polarity Ricker wavelet was used. The more prominent events on the synthetic seismograms have been labelled in order to facilitate comparisons between the geologic models, synthetic seismograms and seismic lines (Figs. 2.A.2.22, 23).

Line 1 (Fig. 2.A.2.20) clearly demonstrates that the pod of Drum Limestone thins dramatically at the north and south ends of the line. The Galesburg Shale is thinnest directly below the thickest Drum Limestone. The top of the Drum Limestone appears to be more irregular than shown on the well log cross sections. This may be due to post Drum erosion. Alternatively, the upper surface may be irregular because the Drum Limestone interfingers with the lowermost Nellie Bly as observed in the Heartland Cement Co. quarry. The cores along this transect, however, show no evidence of a facies relationship between the upper Drum and lower Nellie Bly.

A comparison of the geologic model and the synthetic seismogram for line 2 indicates that tops of the Mound Valley Limestone, Winterset Limestone, unnamed sandstone and a limestone in the upper Nellie Bly(?) Formation, and the base of the unnamed sandstone are manifested as relatively high-amplitude peaks on the synthetic seismogram (Fig. 2.A.2.20). The base of the interpreted channel-fill, in contrast, is represented as a moderate-amplitude trough. Low-amplitude diffractions originate at the edges of these truncated horizons. The complexity of the central part of the synthetic seismogram is increased as a result of the non-vertical incident reflections from the base of the channel which collectively produce the observed classic "bow-tie" effect beneath the base of the channel.

The interpreted seismic line 2 is presented as Fig. 2.A.2.22A. The labelled events were identified on the basis of the synthetic seismogram. The time-depths to the respective horizons are consistent with subsurface control at the Clarkson #2 well site, stacking velocities and check shot survey control. The high degree of correlation between the geologic model, synthetic seismogram and seismic line support the seismic interpretations presented.

As anticipated from the analysis of the synthetic seismogram, the tops of the Mound Valley Limestone, Winterset Limestone, unnamed sandstone and a limestone in the upper Nellie Bly(?)

Formation, and the base of the unnamed sandstone correspond to relatively high-amplitude peaks on the seismic line. The Mound Valley Limestone, Winterset Limestone, unnamed sandstone and Nellie Bly(?) Formation events appear to be correlatable across the seismic line. In contrast, the reflections from the top and base of the unnamed sandstone unit, as correlated, are truncated by an interpreted deeply incised and infilled channel. The base of the interpreted channel fill is correlated as a moderate-amplitude trough. The polarity of this event, and the subtle negative drape across the channel along the Nellie Bly(?) event, suggests that the channel fill is composed predominantly of compacted shales. This thesis has not been independently confirmed by drilling.

One striking feature on seismic line 2 is the dramatic thinning of the Galesburg shale to the north (Fig. 2.A.2.22; at about 65 ms, between the Dennis and Mound Valley Limestones). This is consistent with core and well log data (Fig. 2.A.2.19) and interpreted as confirmation of either the local depositional thinning or erosional thinning of the Galesburg Shale.

Also of significance is the apparent absence of the Drum Limestone along the entirety of seismic line 2. (The absence of Drum Limestone at trace 494 has been confirmed by the Clarkson core.) Our preferred interpretation is that the Drum Limestone was not deposited in this part of the study area. Based on outcrop and shallow well control, we interpret the Drum Limestone to have been deposited as several(?) lobes elongated perpendicular to the edge of the Cherryvale delta. In our opinion, the example seismic line was shot between Drum Limestone lobes, in an area that received only shale deposition (Fig. 2.A.2.17).

Analysis of cores and well logs in the study area suggests that the unnamed sandstone within the Nellie Bly(?) Formation rests unconformably on lower older units. The irregularity of this reflector on the seismic line and the interpreted channel are further evidence of the erosional nature of the lower contact and basal portion of the Nellie Bly(?) Formation.

The seismic line illustrates that stratigraphic complexity of the upper Nellie Bly(?) and overlying units indicated by lack of lateral continuity of events shallower than approximately 45 ms (Fig. 2.A.2.22). This complexity is suggested in the geologic cross section by our inability to correlate the Quivira

Shale(?) north of the Clarkson #2 core (Fig. 2.A.2.19). A shale-filled channel is hypothesized as a partial explanation for the lack of continuity of shallow reflectors based on the similarity of the seismic line and synthetic model data. Channeling in the Nellie Bly(?) Formation may explain the lateral discontinuity of thin limestone and sandstone beds shown on the well logs in Fig. 2.A.2.19.

## Summary and Conclusions

A 12-fold and 2 24-fold high-resolution seismic lines were obtained along an two transects in central Montgomery County, Kansas. The interval from the Mound Valley Limestone to the Quivira Shale(?) was imaged. Ground truth was based on cores and well logs. These data in addition to interpretation of the seismic line were used to construct simplified geologic models. The models were used to construct a synthetic seismic section. The synthetic sections agree well with the original seismic sections. This technique revealed outcrop-scale features in the rocks, including one small channel in the Nellie Bly(?) Formation not previously suspected.

# POROSITY EVOLUTION IN DRUM OOLITE FACIES

## Introduction

A petrographic study of diagenetic characteristics was conducted on selected samples from the skeletal, oolite facies of the Drum Limestone from the Heartland Cement Quarry. This facies was focused on because of its apparent similarity to known reservoir facies in the subsurface of Kansas. 28, 2 inch by 3 inch thin sections were studied using the thin section staining techniques described by Dickson (1965) and standard plain light petrography to determine the different diagenetic features and events and their spatial distribution. Our observations indicate a complex history and spatial distribution of post-depositional diagenetic events that affected the Drum skeletal, oolite facies in the Heartland Cement Quarry. The descriptions and discussion below focus on our initial results of the porosity and cement history for these rocks.

Description and General Stratigraphy of Cements

Isopachous bladed calcite (Cement A): Forms isopachous fringes up to 80 µm thick (Fig. 2.A.2.24 A). This cement is rare, but most common in the lower 30 ft (9.1 m) of the Drum Limestone. The isopachous bladed calcite typically occurs in patches as fringes on adjacent grains. No cements were observed to have precipitated prior to this cement. The isopachous bladed calcite cement is overlain by the medium crystalline, equant clear calcite cement.

Isopachous cloudy, bladed to equant calcite (Cement B): Coarse, equant to bladed, crystals (up to 500 µm long) of cloudy calcite is abundant in the upper part (upper 1/4) of the skeletal oolite grainstone facies in the Heartland Cement Quarry where it fills nearly all (>95%) of original void space (Fig. 2.A.2.24 B, C). The cement decreases in abundance downward, where it occurs primarily in large shelter pores. Locally, the cloudiness appears to be the remnant ghost structure of an originally fibrous cement. In these areas, coarse crystals are probably a replacement of an isopachous, fibrous, botryoidal aragonite(?) cement. The cloudy, originally fibrous, cement occurs as isopachous crusts and as uneven coatings on allochems. The isopachous morphology is most obvious in shelter voids where the original pore diameter is much greater than cement thickness. In intraparticle voids this cement (cement B) is manifest as an medium- to coarse-crystalline equant, cloudy, pore-filling calcite cement. In large pores alternating zones of turbid and less turbid cement are apparent. Cement B was not observed in contact with the isopachous bladed calcite cement and they could have been precipitated at essentially the same time. Cement B is overlain by coarse, clear, equant calcite (cement D) and medium-crystalline, equant, clear calcite cements (cement E).

Syntaxial calcite (Cement C): Large (up to 400 µm) clear crystals in optical continuity with echinoderm grains occur throughout the skeletal oolite facies, but are most common in the upper 1/4 of the oolite. This cement does not occur on echinoderm grains with oolitic coatings or micrite rims. Interference with the growth of cloudy, isopachous cement suggests they were precipitated simultaneously.

Coarse-crystalline, clear, equant calcite (Cement D): Large (up to 400 µm) clear, equant calcite crystals overlie the isopachous cloudy cement (cement B) in large voids that were not completely filled by the isopachous cloudy calcite cement (Fig. 2.A.2.24 B). Most crystals of coarse clear equant calcite are in optical continuity with the underlying crystals of cloudy calcite.

Medium-crystalline, clear, equant, calcite (Cement E): Cement composed of small (average approximately 100 µm) equant calcite crystals is the most common cement in the skeletal oolite grainstone facies in the Heartland Cement Co. Quarry, and fills most original void space in the lower 3/4 of the Drum Limestone in the Heartland Cement Quarry (Fig. 2.A.2.24 D). It clearly overlies the isopachous bladed calcite (cement A), but its relationship to the coarse, cloudy isopachous calcite (cement B) is not clear. Downward through the Drum Limestone in the quarry (and even within individual thin sections) there is a gradual change from coarse turbid and clear calcite to medium equant calcite suggesting that this cement may, in part, be a product of neomorphism.

Coarse, equant, clear, ferroan calcite (Cement F): Composed of coarse (up to 300 µm) equant crystals with sweeping extinction (Fig. 2.A.2.24 E). This cement has only been observed in interparticle pores in the uppermost 10 ft (3 m) of Drum Limestone where other cements are absent, and the sediment has been highly compacted. In addition some grains have been neomorphosed to ferroan calcite. Ferroan dolomite fills molds in rock supported by this cement, and therefore probably was precipitated after the ferroan calcite.

Baroque ferroan dolomite (Cement G): Medium to coarsely crystalline with sweeping extinction; stains blue with potassium ferricyanide (Fig. 2.A.2.24 C). The dolomite is the last pore-filling cement occurring stratigraphically above the coarse, clear calcite (cement D) and the coarse, clear, ferroan cements (cement F). The dolomite occurs in many secondary pores throughout the skeletal oolite grainstone facies and also occurs locally as a replacement of grains and previous cements.

### Paragenetic Sequence of the Drum Oolite

A generalized paragenetic sequence and spatial distribution of diagenetic features has been determined for the skeletal oolite facies. It appears from initial observations that this general sequence and distribution can vary significantly over very short lateral and vertical distances. However, the sequence of events and distribution patterns presented herein are useful in a general understanding of heterogeneities within a potential reservoir facies, comparing the Drum sequence and features to similar facies that are reservoirs, and they form a good foundation on which to conduct further, more detailed diagenetic studies.

The relative timing of diagenetic events within the skeletal oolite facies is as follows:

1) Precipitation of isopachous bladed (probably originally as fibrous, botryoidal aragonite) and bladed-to-equant marine cements shortly after oolite deposition (cements A, B).

2) Precipitation of syntaxial cement overgrowths (cement C) locally on crinoid fragments, possibly concomitant precipitation with cements A and B.

3) Initiation of early compaction that ends prior to precipitation of cement F.

4) Selective dissolution of aragonitic allochems (e.g. ooids, mollusc fragments); early marine isopachous cements (cements A and B) were not affected by dissolution.

5) Replacement of cements A, B and C?, and allochems, and cement precipitation in primary and secondary pores by medium- and coarse-crystalline, clear, equant calcite (cements D and E).

6) Selective precipitation and replacement by ferroan calcite (cement F).

7) Selective precipitation and replacement by ferroan baroque dolomite (cement G).

8) Late stage compaction and dissolution.

In addition to the above general paragenetic sequence of events for the skeletal oolite facies of the Drum Limestone exposed in the Heartland Cement Quarry, this facies can be further divided into three general diagenetic facies based on a vertical distribution pattern of dominant diagenetic features described above. These three diagenetic facies are as follows:

Diagenetic Facies 1: The upper most few feet (from the top of the oolite down to a maximum of 10 ft [3 m]) are highly compacted, lack early cements, and contain abundant late cement (cements F and G) (Fig. 2.A.2.24 E).

Diagenetic Facies 2: The rest of the upper third (down to approximately 25 ft [7.6 m] below the top of the skeletal oolite grainstone) is dominated by the isopachous cloudy calcite cement (cement B), and is not compacted (Fig. 2.A.2.24 B, C).

Diagenetic Facies 3: The lower two thirds of the skeletal oolite grainstone is cemented dominantly by the medium- and coarse-crystalline equant calcite (cements D and E), and is not compacted (Fig. 2.A.2.24 D).

Diagenetic facies 1 (the uppermost facies) is characterized by highly compacted sediment (pressure solution along grain-to-grain contacts is common, many grains are cracked, and oolitic coatings are spalled off of grains) and coarse ferroan calcite cement (cement F) with minor amounts of ferroan dolomite cement (cement G) within rare oomolds. The high degree of compaction of this facies is consistent with the lack of early cements. Samples from this diagenetic facies have been recovered as low as just below the lowest shale within the upper part of the Drum Limestone. In the Heartland Cement Quarry core only the upper 2 or 3 ft (1 m) of Drum are within this diagenetic facies. Ooids and fossils are generally well-preserved, however ooids have been neomorphosed to ferroan and nonferroan calcite. Crystals within ooids generally follow the concentric laminations, but some cut across laminations.

Diagenetic Facies 2 (the middle facies) occurs immediately below the zone of compacted grainstone of diagenetic facies 1. The contact between these two facies is sharp. Diagenetic facies 2 consists of approximately 10 - 20 ft (3 - 6 m) of uncompacted grainstone in which the most pervasive cement is cloudy isopachous calcite (cement B). Due to the extreme thickness of this cement (approximately 500 µm), the isopachous morphology can only be observed in large shelter voids below fossils (Fig. 2.A.2.24 B, C). The cement was likely originally fibrous and has been subsequently neomorphosed to a bladed to equant morphology. Overlying the isopachous calcite is clear equant calcite (cements D and E) and then ferroan dolomite cement (cement G). Ooids are well preserved with many thin concentric layers that are along crystal contacts or are preserved as ghost structures within crystals. Porosity generally decreases downward in diagenetic facies 2. Primary porosity is currently present only in the largest pores that were not completely filled with cement (Fig. 2.A.2.25 A). Most remaining porosity is moldic. Originally, aragonite allochems such as ooids and molluscs were selectively dissolved (Fig. 2.A.2.25 C, D). Other allochems such as brachiopods, echinoderms, and bryozoans are well-preserved. Most pores are isolated molds so permeability is low.

The boundary between diagenetic facies 2 and diagenetic facies 3 (the lowest facies) is gradational with the isopachous bladed to equant calcite cement (cement B) characteristic of diagenetic facies 2 becoming less common and medium- to coarse-crystalline equant calcite (cement D and E), characteristic of diagenetic facies 3, becoming the primary cements. As these latter cements becomes more abundant downward, the nature of neomorphism in ooids changes from relatively large crystals with crystal boundaries that follow ooid laminations to ooids that are neomorphosed to calcite crystals similar in morphology to the medium-crystalline equant calcite cement. The medium-crystalline equant cement may therefore represent, in part, a product of neomorphism. As is the case in diagenetic facies 2, permeability is generally low, but is locally increased by two factors: degree of dissolution and crushing of molds (Fig. 2.A.2.25 C). Degree of dissolution generally increases downward in diagenetic facies 2 and 3, but also ranges widely within a single thin section. Dissolution may have been affected by the permeability of the sediment after early cementation. Where dissolution is maximized, intergranular cements are partly dissolved, producing pore throats between adjacent molds. Permeability is also maximized in cm-thick zones of collapsed oomolds. These zones occur preferentially along the bases of beds where grain size was apparently small, and sorting was good.

### Discussion

The contrast in cementation history between the upper (diagenetic facies 1) and lower part (diagenetic facies 2 and 3) of the Drum Limestone in the Heartland Cement Quarry may be the cause of several factors including early marine cement distribution with the resultant porosity and permeability trends, variability in effects of early compaction and selective dissolution, and possibly the level of an relatively early, ancient meteoric water table.

It appears the early marine cements (cements A,B, and C) precipitated in the lower 3/4 of the Drum Limestone prevented significant early compaction of these rocks in contrast to the upper 10 ft (3 m) of the Drum Limestone in which these early marine cements are absent and the rocks experienced significant early compaction. Although the original depositional facies were essentially the same, the lack of marine cements in the upper part may indicate changing environments and/or change in relative sea level that would have prevented marine cement precipitation in these rocks. The increase in shale in the upper part may indicate a relative rise in sea level.

Early dissolution, replacement fabrics and precipitation of medium- to coarse-crystalline clear, equant cement (cements D and E), probably reflecting a fresh water, phreatic environment, affected only the lower 3/4 of the Drum Limestone facies and not the upper 1/4. This may reflect differences in porosity/permeability due to early compaction essentially making the upper 1/4 rocks an aquitard to the early meteoric waters. Additionally the shale lenses and seams in the upper 1/4 of the oolite may have reduced permeability. The aquitard hypothesis seems unlikely because of the extensive replacement and cementation by later ferroan calcite and dolomite (cements F and G) that occurred in the upper 1/4 Drum rocks likely in an anoxic(?) burial environment. Alternatively, the distribution of early dissolution and precipitation of cements D and E may reflect an ancient water table; the upper limit of the water table occurred at the sharp boundary between the lower 3/4 (diagenetic facies 2 and 3) and upper 1/4 (diagenetic facies 1). However, no features suggestive of a vadose environment (e.g meniscus cements, pendant cement fabrics, vadose silt) nor of subaerial exposure have been identified to date in the upper 1/4 Drum rocks to substantiate this hypothesis. A third alternative is that cements A,B,C,D and E were all precipitated prior to the deposition of the upper 1/4 of Drum oolite. This would suggest that there was a depositional hiatus and incursion of a fresh water lens likely tied into a relative sea level drop prior the deposition of the upper 1/4 of Drum oolite. The upper 1/4 of Drum oolite facies would have been deposited during the subsequent transgression. However, to date, no erosional truncation surface, subaerial exposure features, nor transgressive lags have been recognized at the boundary between the lower 3/4 and upper 1/4 of Drum in outcrop, handsample, or thin section.

Similarly, no observations have been made from thin sections, to date, of truncation of cements A,B,C,D or E at this boundary nor of inclusion of any of these cements in clasts in the upper 1/4 Drum oolite that would support a depositional break between the lower 3/4 and upper 1/4 of Drum oolite.

It is clear that much detailed diagenetic and geochemical work will be necessary to further document the paragenetic sequence and understand the processes and environments important in the diagenetic evolution of the Drum oolite facies of the Heartland Cement Quarry. At this stage of the study, it appears likely that much of the cementation and porosity creation/occlusion is related to early marine cements and to meteoric cements likely tied into a relative sea level drop during or shortly after deposition of the Drum skeletal, oolite facies. A relative sea level drop just after Drum oolite facies deposition may be supported by evidence from outcrop, core, well logs and high resolution seismic data that indicates the upper Drum Limestone experienced, at least locally, significant erosion possibly due to shallower marine conditions related to a relative fall in sea level.

The diagenetic history of the Drum oolite is very similar to the diagenetic history of the oolitic reservoir in the Swope Sequence of the Victory Field. The primary difference is that the Victory Field lacks the cement that occur in large shelter voids beneath fossils in the Drum, such as cements B and D. Thin sections of well-sorted oolite from the Drum Limestone at the Heartland Cement Co. Quarry are indistinguishable from thin sections from cores and cuttings of reservoir facies in the Victory Field. This suggests patterns of porosity zones observed on Drum oolite outcrops may be useful for developing models of fluid flow in Lansing-Kansas City Group oolitic petroleum reservoirs.

## SUMMARY

An integrated study incorporating sedimentologic, stratigraphic, diagenetic, and high resolution seismic data was conducted on the Drum Limestone in Montgomery County, a potential surface and shallow subsurface analog for oolitic reservoirs in the Lansing and Kansas City groups in central and western Kansas. The goals of the project were to determine the sedimentologic and general diagenetic history of the Drum skeletal oolite facies, to determine the facies and geometry relationships of the

Drum Limestone with associated strata and to determine the controlling factors for deposition and diagenesis of the Drum Limestone.

The Drum Limestone in Montgomery County was deposited on a surface with pre-existing topography that resulted from deposition of underlying units, chiefly the Dennis Limestone and Cherryvale Shale. A broad, flat shelf existed to the north. Near Independence there was a shelf edge that corresponded to the southern edge of a major lobe of the Cherryvale delta. Drum Limestone deposition consisted of four facies from base to top: 1) A thin (generally less than 1 ft [0.3 m]) intraclastic limestone that was deposited during transgression; 2) a deeper water, sparsely fossiliferous interbedded shale and laminated limestone; 3) fossiliferous wackestone, packstone, and stromatolites that were deposited in shallow-water, normal marine to restricted conditions; and 4) cross-bedded skeletal oolite grainstone deposited in shallow-water marine conditions. The contact between the fossiliferous wackestone to packstone and grainstone is sharp, and may have been locally subaerially exposed. Basinward of the depositional shelf edge the oolite thickens from under 20 ft (6.1 m) on the shelf, to 50 ft (15.2 m), and then thins southward to a pinch-out. The fossiliferous packstone to wackestone has not be observed basinward of the depositional shelf edge. The interbedded shale and carbonate mudstone thickens basinward, and the upper part becomes increasingly bioturbated likely indicating increasing oxygenated conditions associated with shallowing at the end of Drum deposition. Locally, upper Drum strata were eroded possibly as a result of a relative lowering of sea level.

High resolution seismic studies were conducted to study geometries and test correlations of Drum and associated strata in the subsurface. The seismic data and synthetic modeling confirmed most observations from outcrop, core and well log data. The seismic data proved most useful for detecting local and overall thickening and thinning patterns in some strata and for detecting outcrop-scale significant erosion of Drum and post-Drum strata.

A petrographic study of diagenetic characteristics was conducted on samples of the Drum skeletal oolite grainstone facies from the Heartland Cement Quarry because of the similarity of this facies to known reservoir facies in the subsurface of Kansas. A complex history of cementation, dissolution and compaction affected this facies and resulted in a variable distribution of diagenetic features.

Despite the spatial distribution complexities, the skeletal oolite grainstone facies can be divided into three general diagenetic facies based on vertical distribution pattern of dominant diagenetic features. The upper zone (consisting of up to 10 ft [3 m] of Drum Limestone) lacks early cements, is significantly compacted, and contains only late ferroan calcite and dolomite cements and replacement fabrics. The middle and lower zones were relatively unaffected by early compaction due to cementation by early marine and meteoric phreatic cements. Moldic porosity generally increases downward through the upper most 15 ft (4.6 m) of Drum Limestone. Permeability is greatest where oomolds have collapsed. A reservoir model based on the Drum Limestone would indicate that fluid would flow along the zones of collapsed oomolds which occur primarily along bedding contacts. These zones would form conduits of fluid flow, potentially leaving large amounts of bypassed oil.

Several hypotheses could explain the paragenetic sequence and spatial distribution of diagenetic features. It appears likely that much of the cementation and porosity evolution is related to early marine cements and meteoric cements related to a relative sea level fall during or shortly after Drum skeletal oolitic facies deposition.

The integrated methods used in this study have resulted in a better understanding of depositional and diagenetic features associated with the Drum Limestone and a better understanding of potential reservoir characteristics and heterogeneities within the Drum skeletal oolite grainstone facies. The methods demonstrated in this study should prove useful in the study of similar, potential and actual reservoir facies.

## ACKNOWLEDGMENTS

This project was funded by a grant from the Department of Energy. We are grateful to land owners who gave us access for coring and seismic. These include Mr. Warren Ferrell, Mr. Jesse Clarkson, Mrs. Leona Bredehoft, Williams Brothers Pipeline Company, and the Heartland Cement Co. Additional wireline well logs were provided by T. L. Carroll Enterprises, Inc. and Geomap Inc. Don

Thompson of TYCO provided assistance in locating buried pipelines.

## TECHNOLOGY TRANSFER - DRUM LIMESTONE PROJECT

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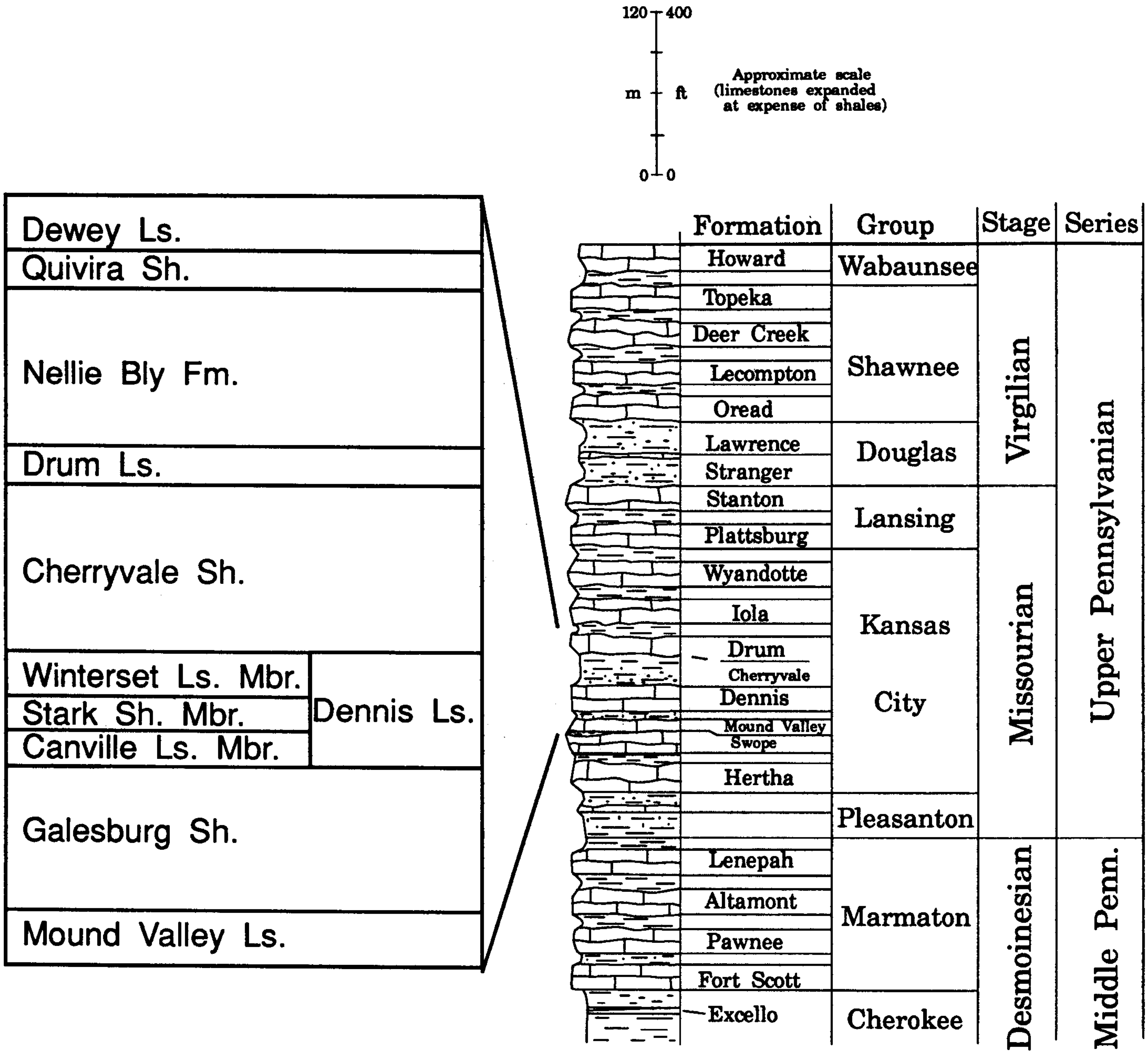


Figure 2.A.2.1. Scematic diagram of the stratigraphy in the study area. Modified from Heckel (1977).

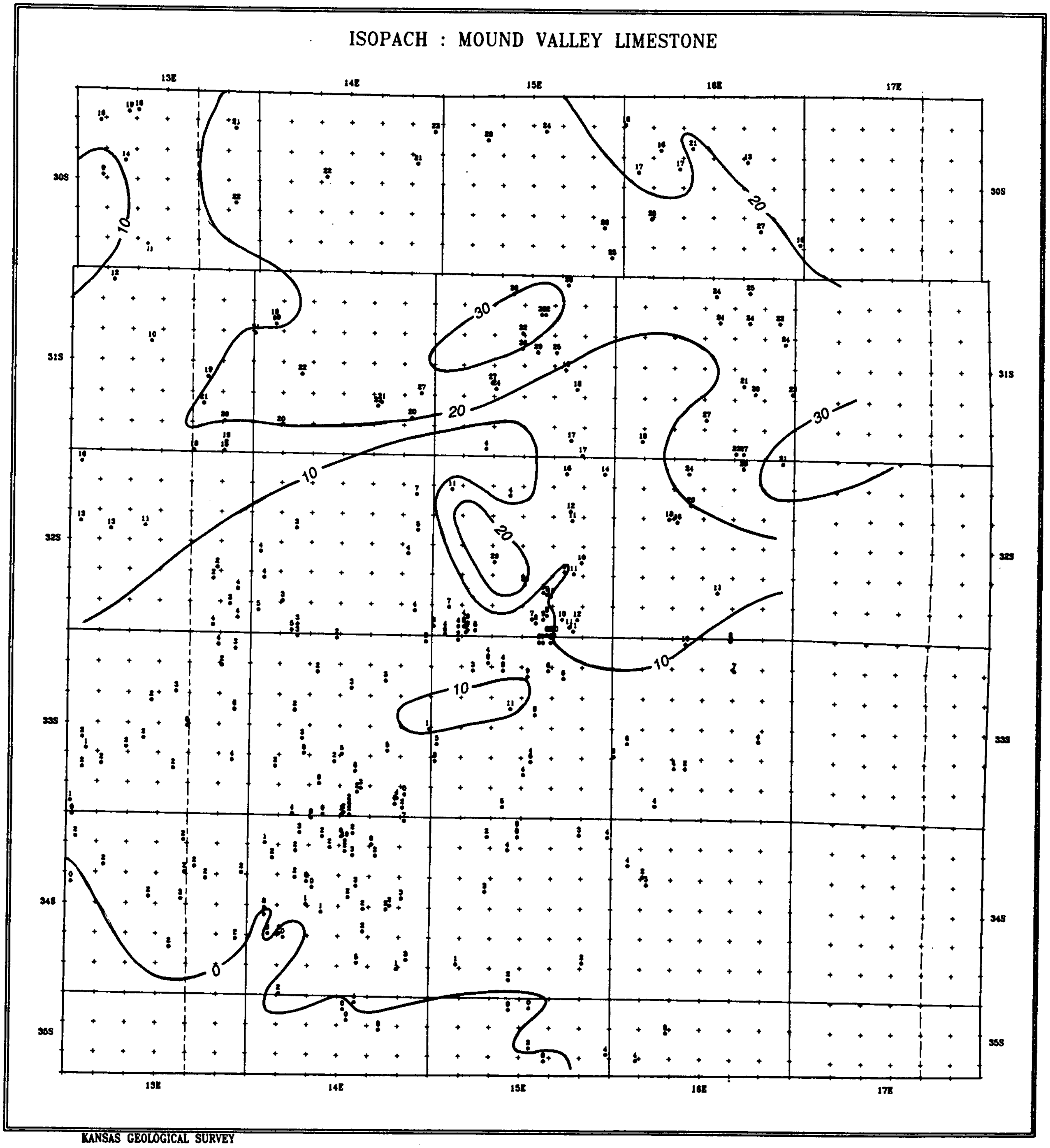
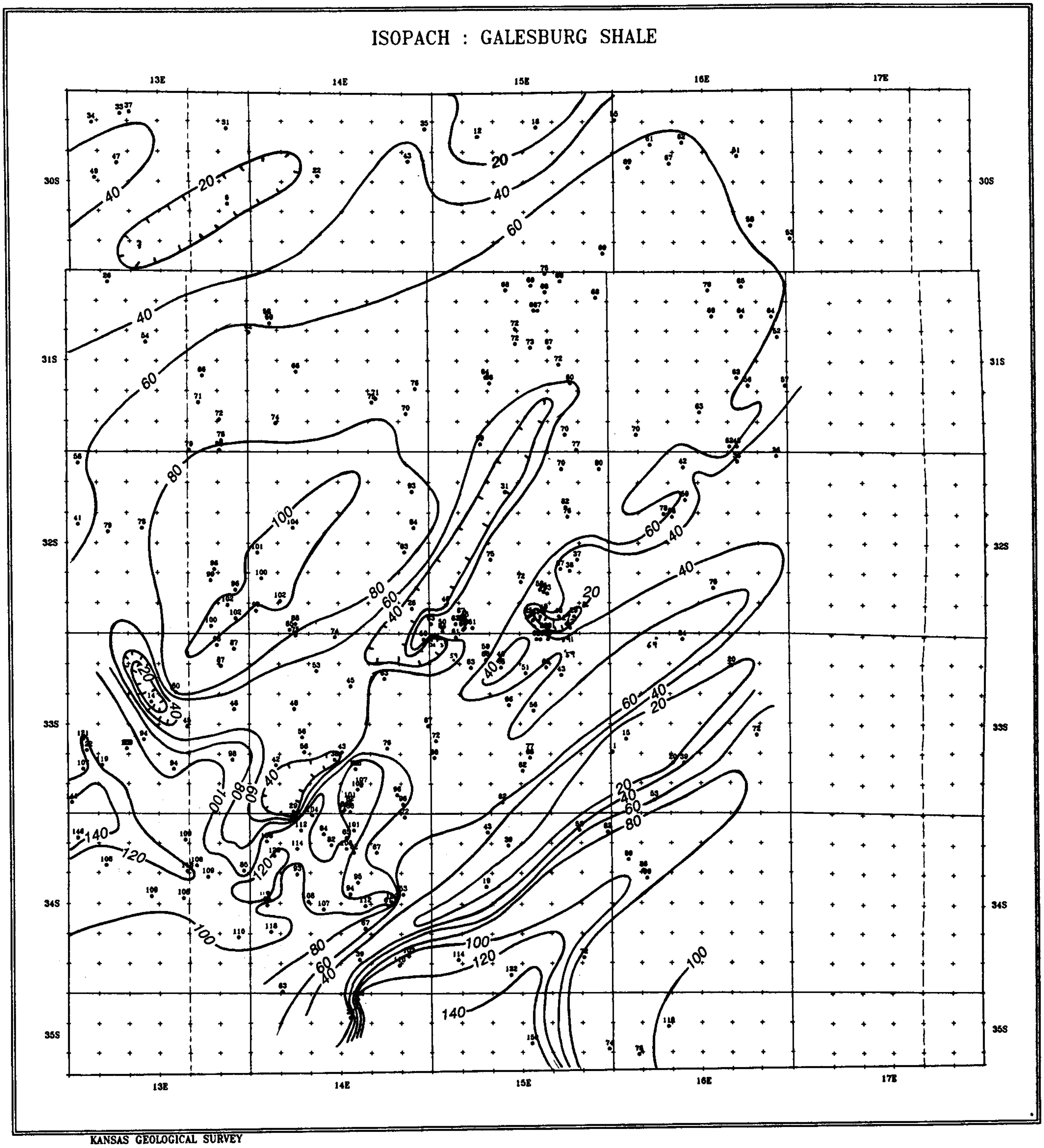
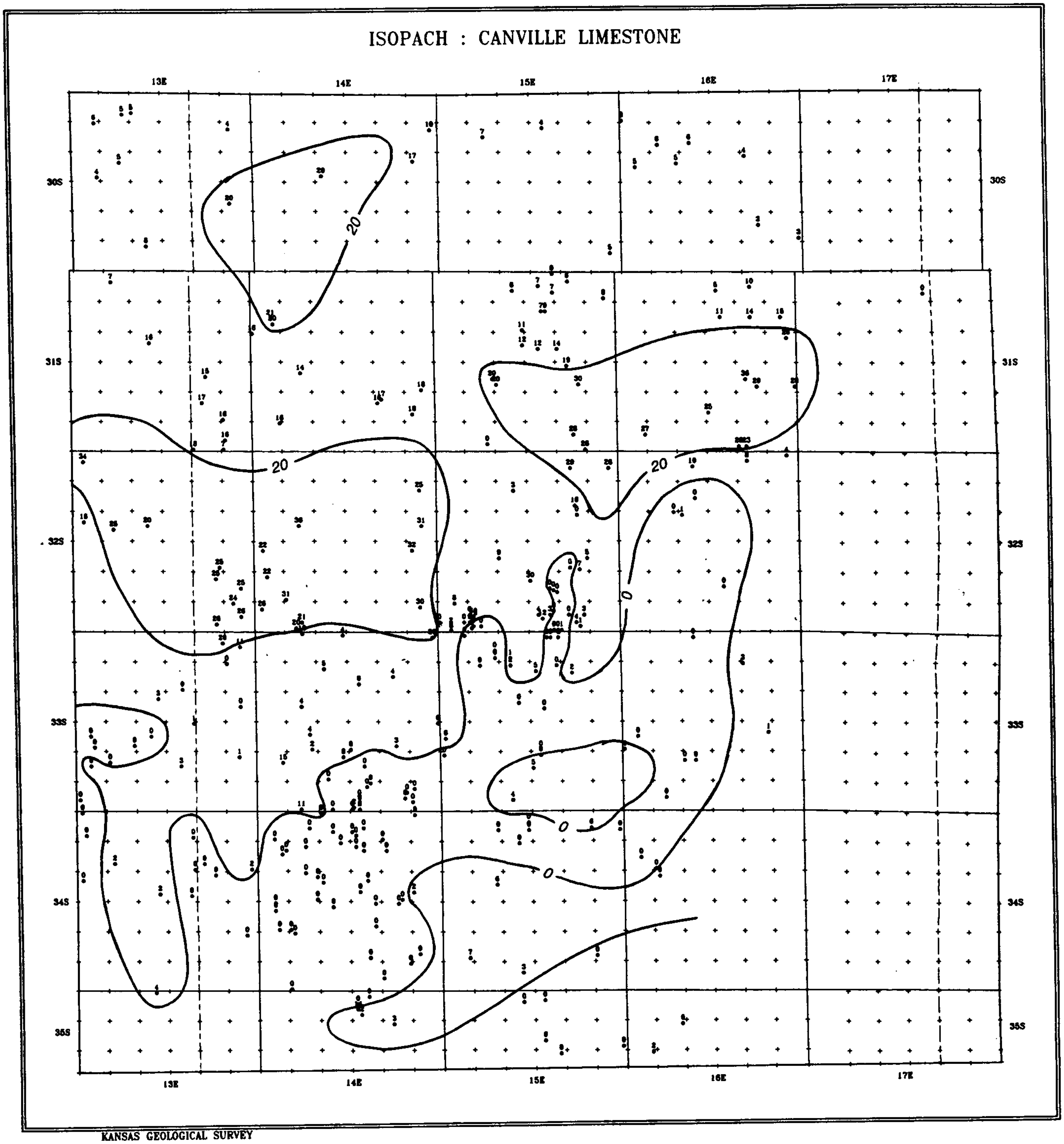


Figure 2.A.2.2. Isopach map of the Mound Valley Limestone in the study area. Dots indicate control points. Contour Interval is 10 ft.



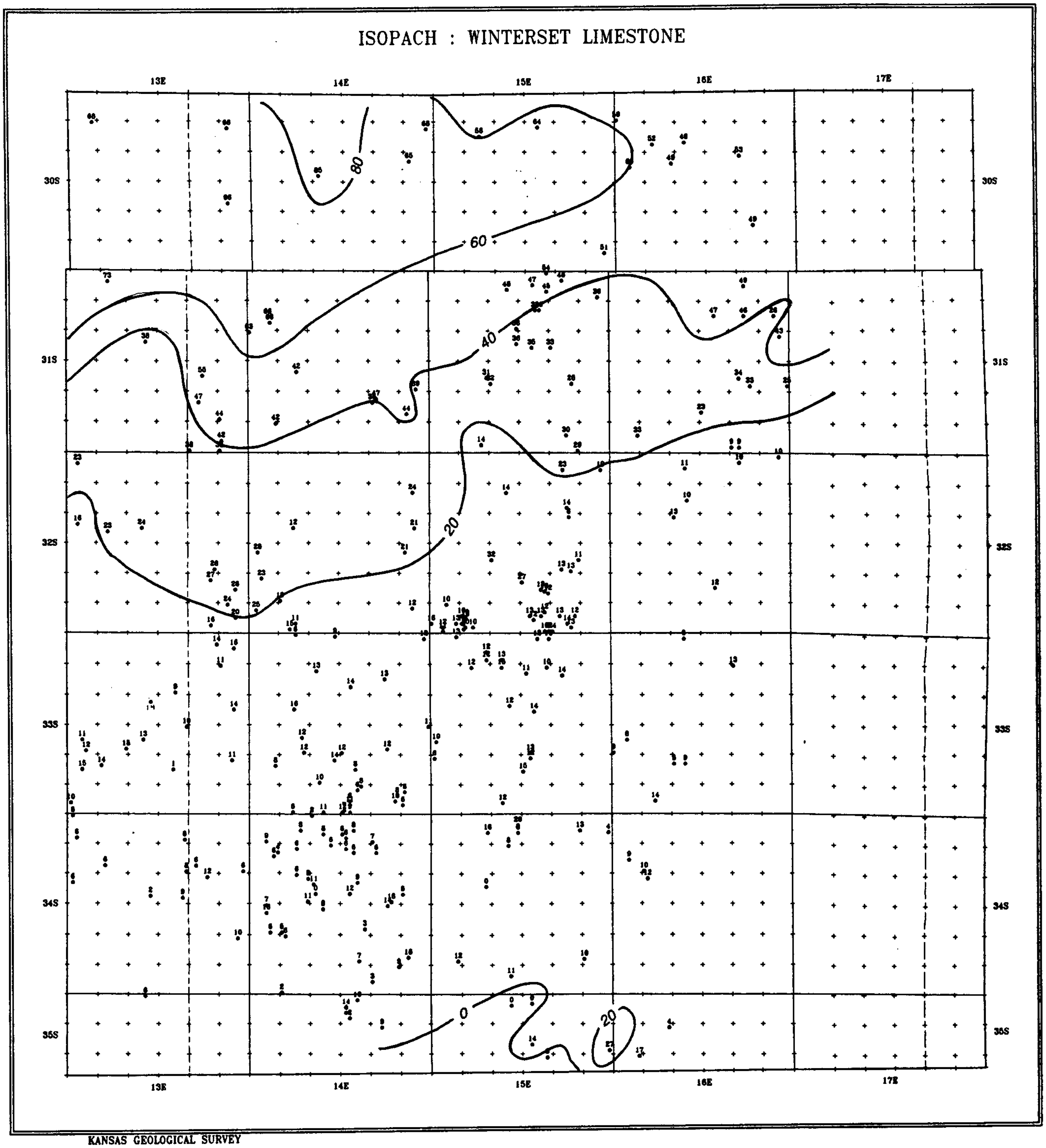
KANSAS GEOLOGICAL SURVEY

Figure 2.A.2.3. Isopach map of the Galesburg Shale in the study area. Dots indicate control points. Contour Interval is 20 ft.



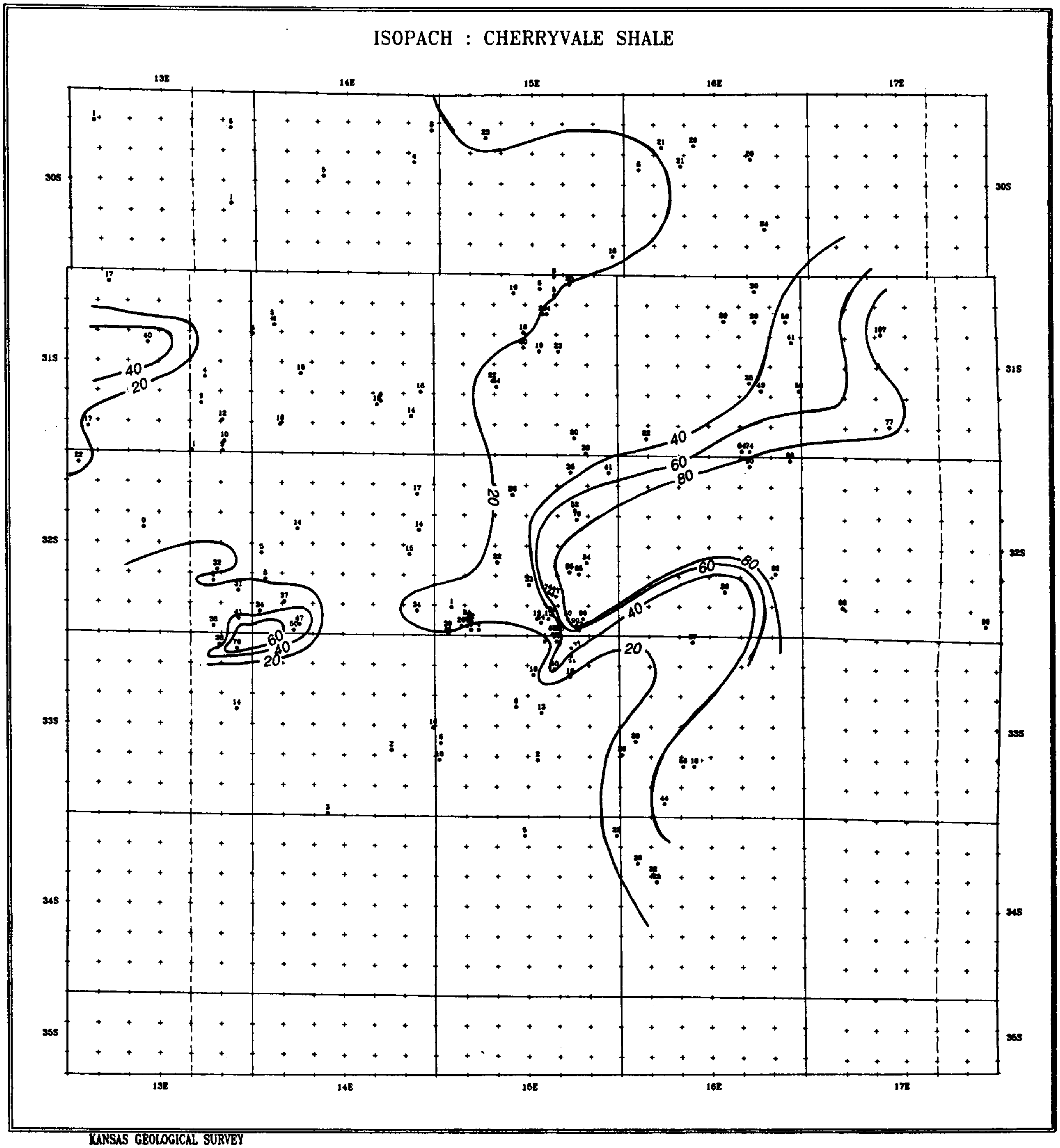
KANSAS GEOLOGICAL SURVEY

Figure 2.A.2.4. Isopach map of the Canville Limestone in the study area. Dots indicate control points. Contour Interval is 20 ft.



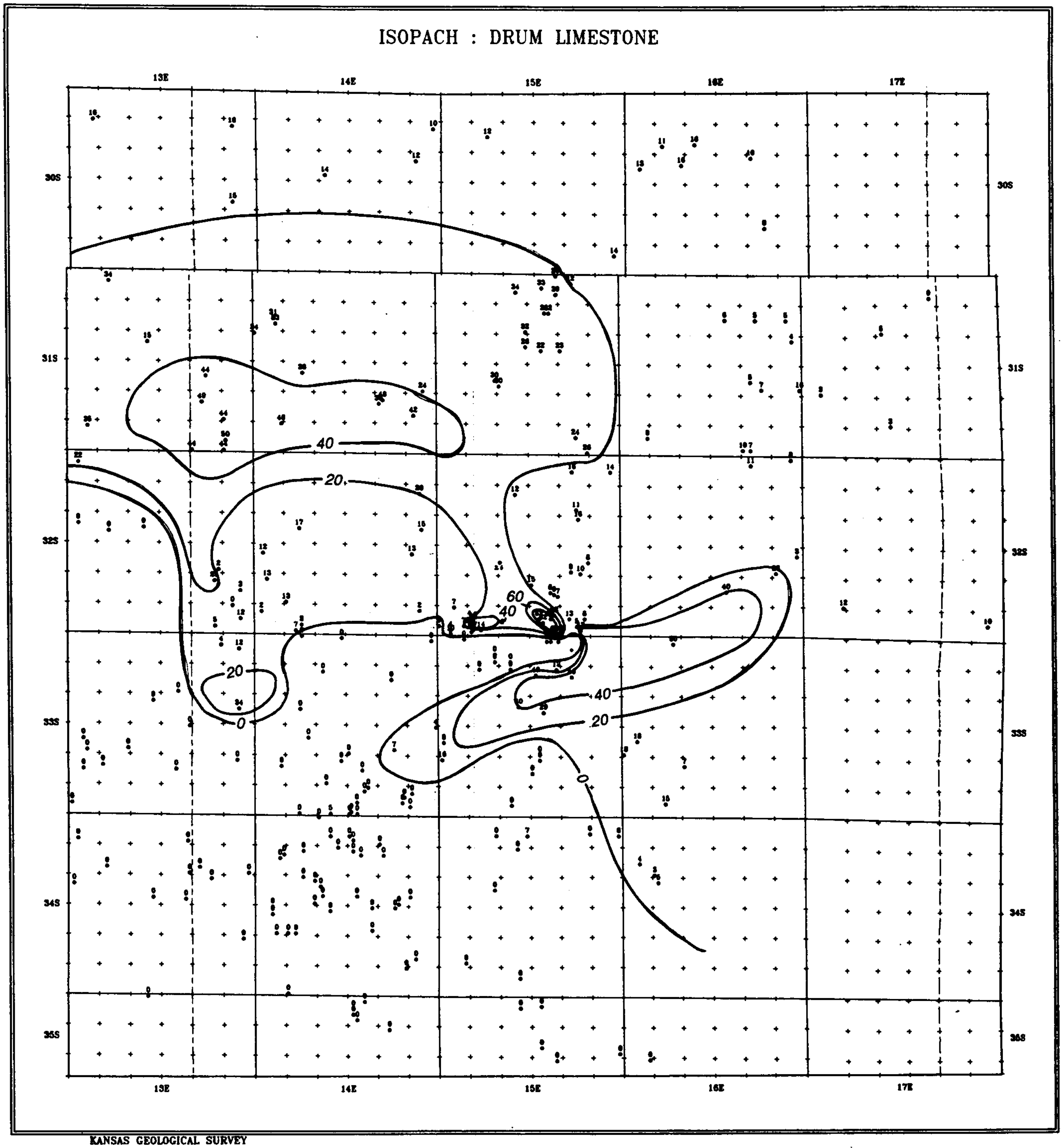
KANSAS GEOLOGICAL SURVEY

Figure 2.A.2.5. Isopach map of the Winterset Limestone in the study area. Dots indicate control points. Contour Interval is 20 ft.



KANSAS GEOLOGICAL SURVEY

Figure 2.A.2.6. Isopach map of the Cherryvale Shale in the study area including the interbedded limestone and shale facies. The thick lobe in the southeast portion of the map is largely due to thick interbedded limestone and shale facies. Dots indicate control points. Contour Interval is 20 ft.



KANSAS GEOLOGICAL SURVEY

Figure 2.A.2.7. Isopach map of the Drum Limestone in the study area not including the interbedded limestone and shale facies. Dots indicate control points. Contour Interval is 20 ft.

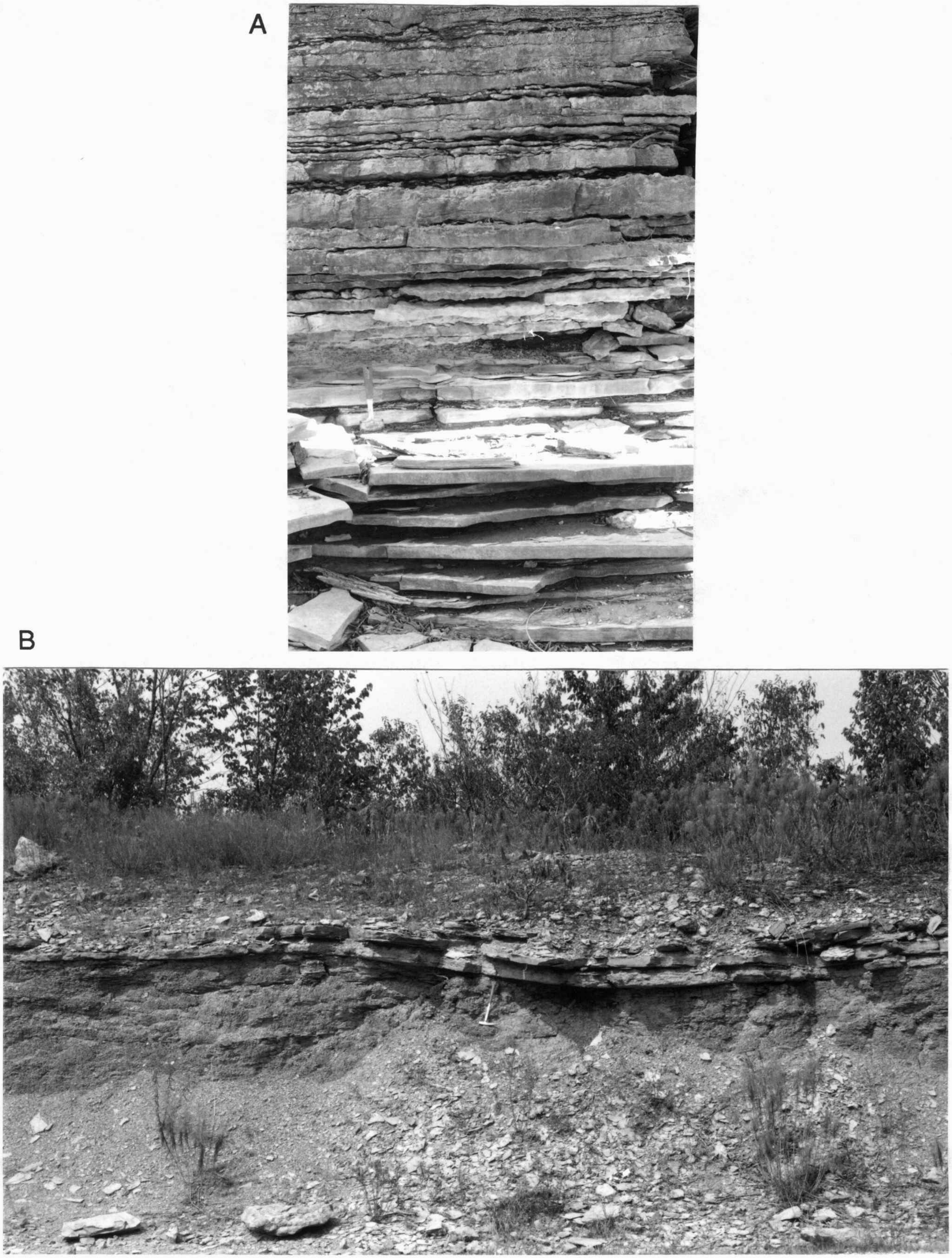


Figure 2.A.2.8. A. Photograph of interbedded limestone and shale facies below the oolite in the Drum Limestone at location IND-2. Upper beds in photograph are bioturbated. Note hammer at left for scale. B. Photograph of the contact between the lowest limestone bed of the Drum Limestone (above hammer) and the underlying Cherryvale Shale at location LIB-5. The contact may be erosional at this location.

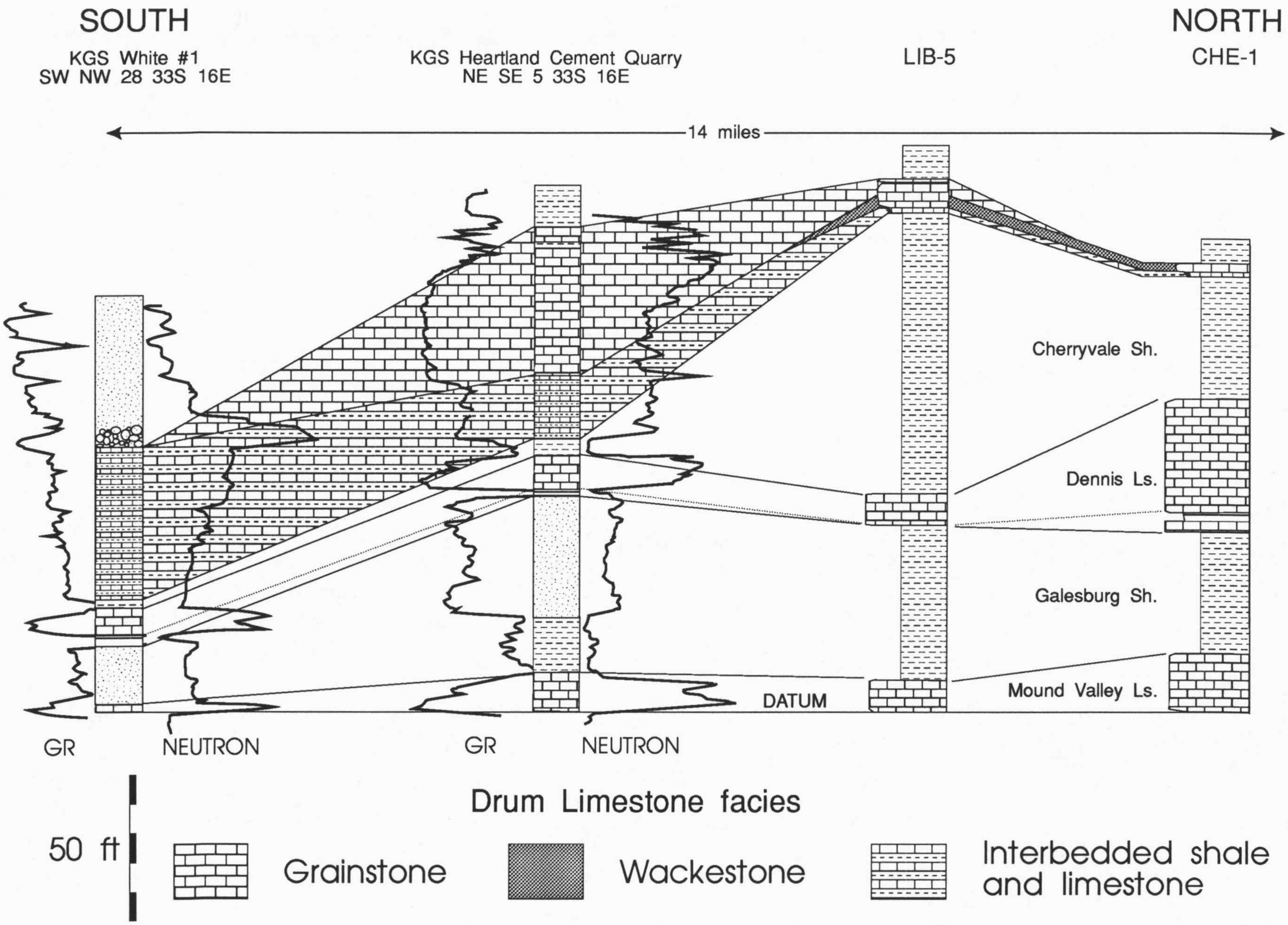


Figure 2.A.2.9. Cross section of the Drum Limestone along the outcrop belt. The KGS White #1 core is adjacent to outcrop location IND-2. See Appendix C for outcrop locations.

Figure 2.A.2.10. Photograph of cross sections through stromatolites from location CHE-1. Thickness of interval in photograph is 2 ft. Stromatolites photographed on overturned block, but are presented in presumed original orientation.

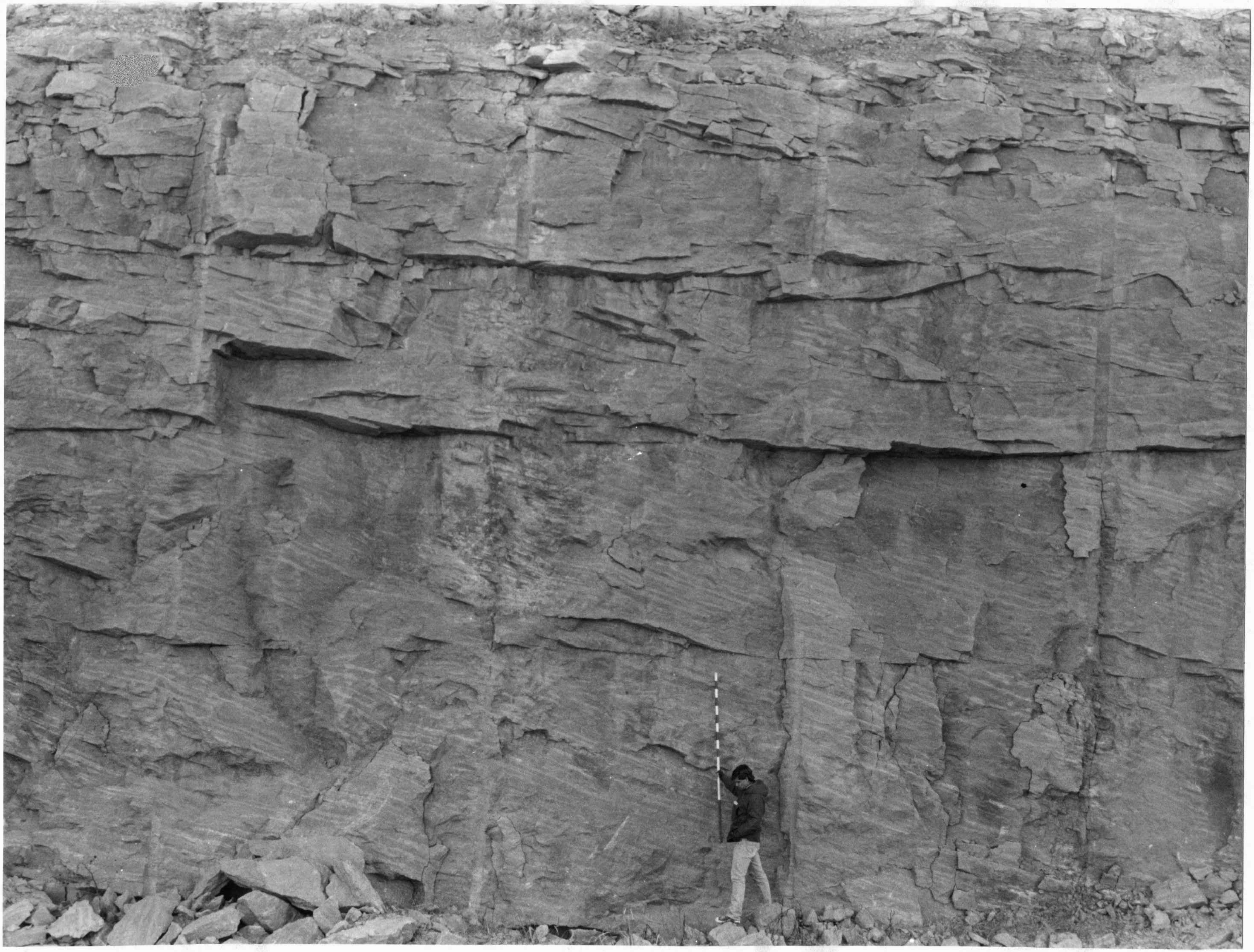


Figure 2.A.2.11. Photograph of cross bedded oolite in the Drum Limestone in the Heartland Cement Quarry. Quarry high wall is oriented west-north-west (see Fig. 2.A.2.12). Staff is 2 meters long.

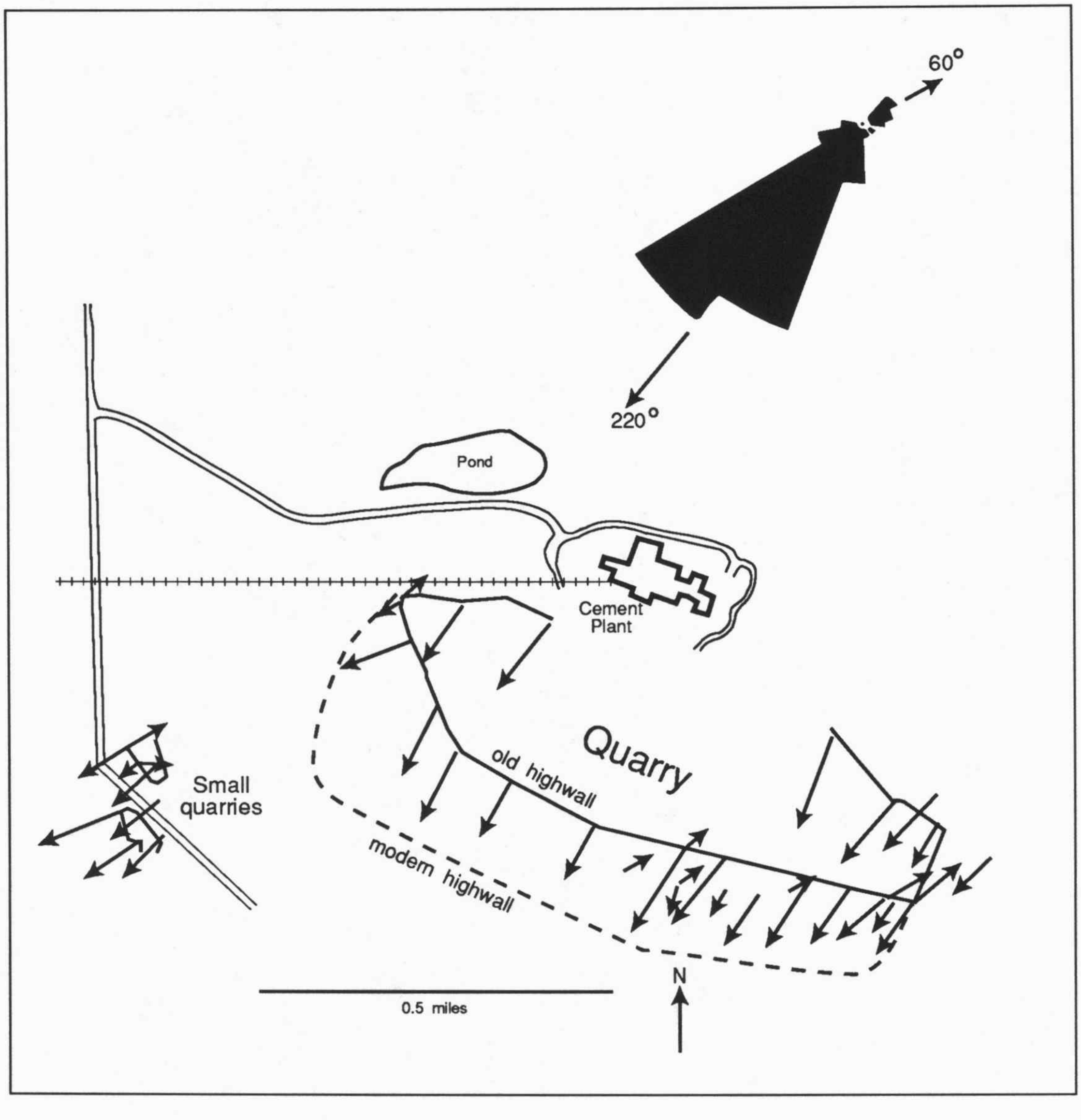


Figure 2.A.2.12. Map of the Heartland Cement Quarry showing cross bed directions from Hamblin (1969). Arrows indicate individual cross bed measurements.

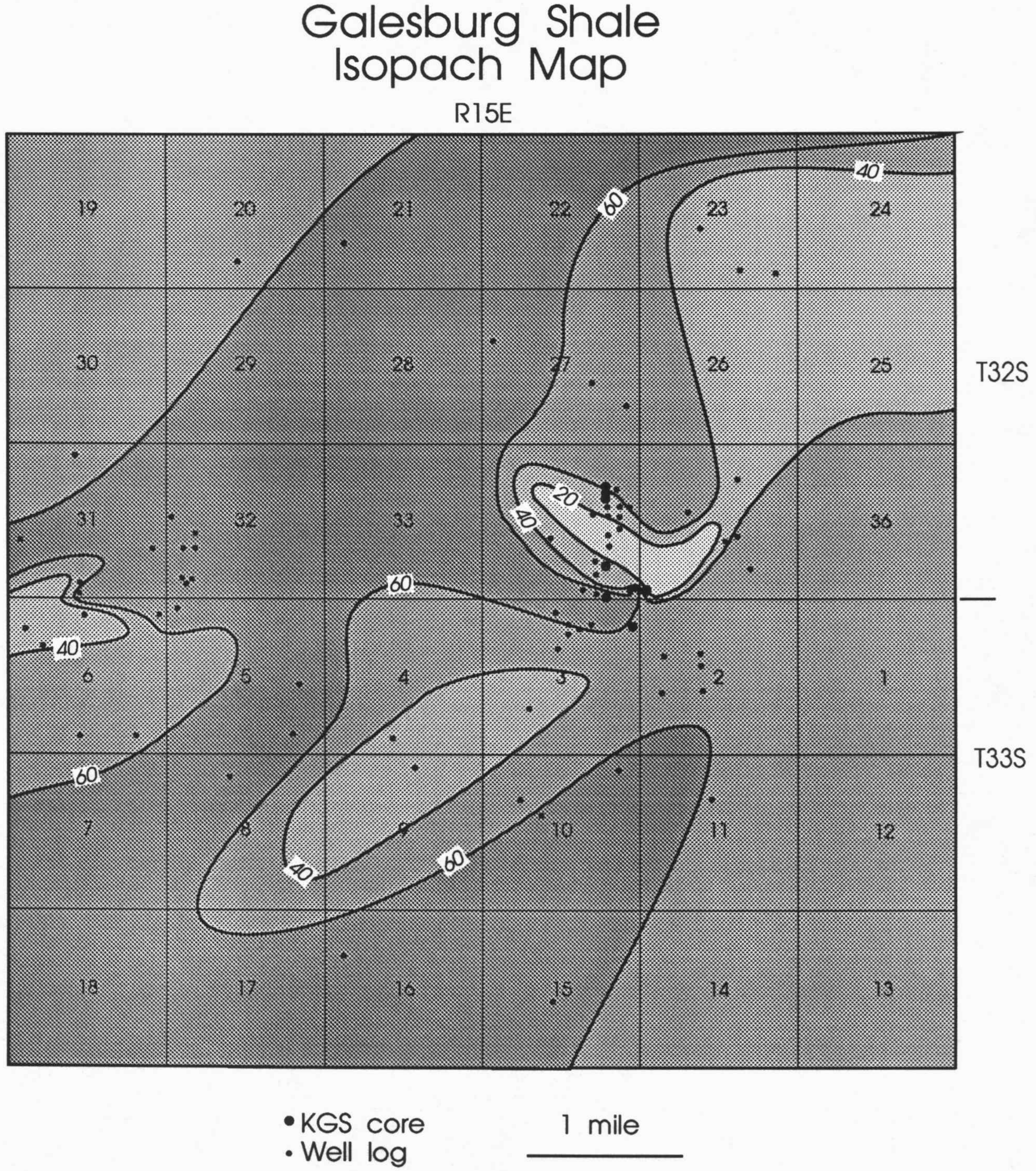


Figure 2.A.2.13. Isopach map of the Galesbug Shale in a portion of the study area in central Montgomery County. Thicknesses are in feet.

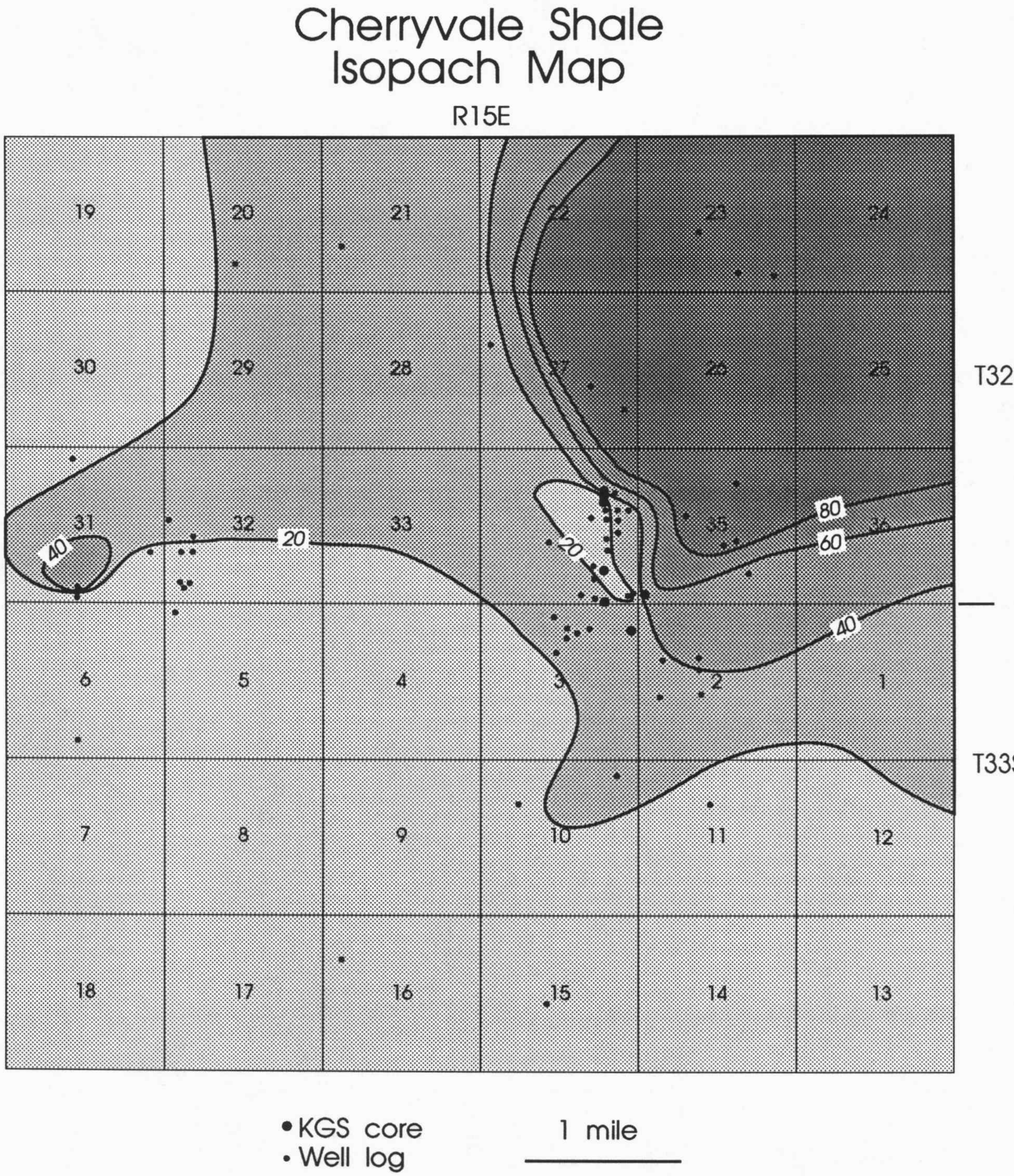


Figure 2.A.2.14. Isopach map of the Cherryvale Shale in a portion of the study area in central Montgomery County. Thicknesses are in feet.

# Drum Limestone Isopach Map

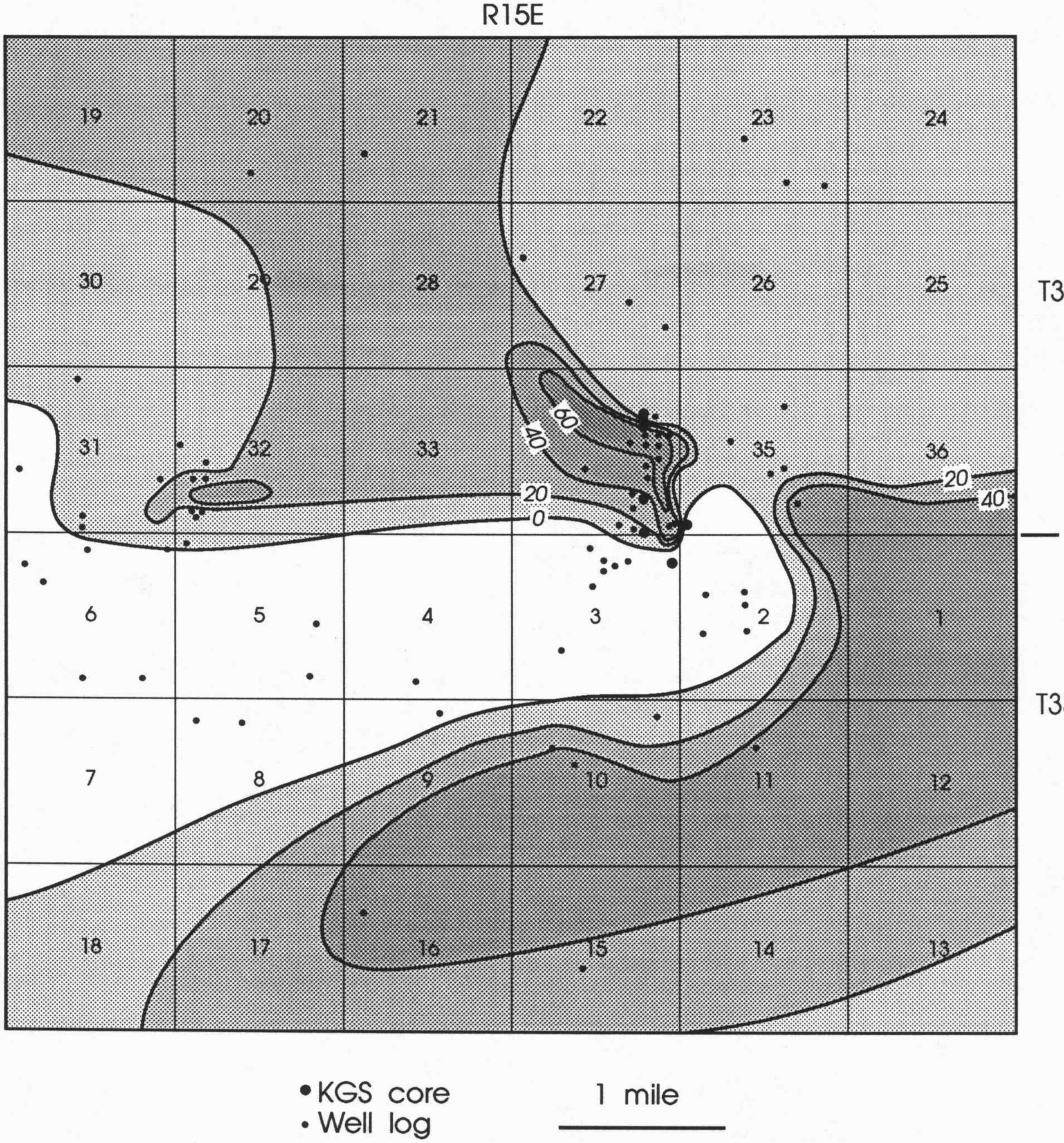
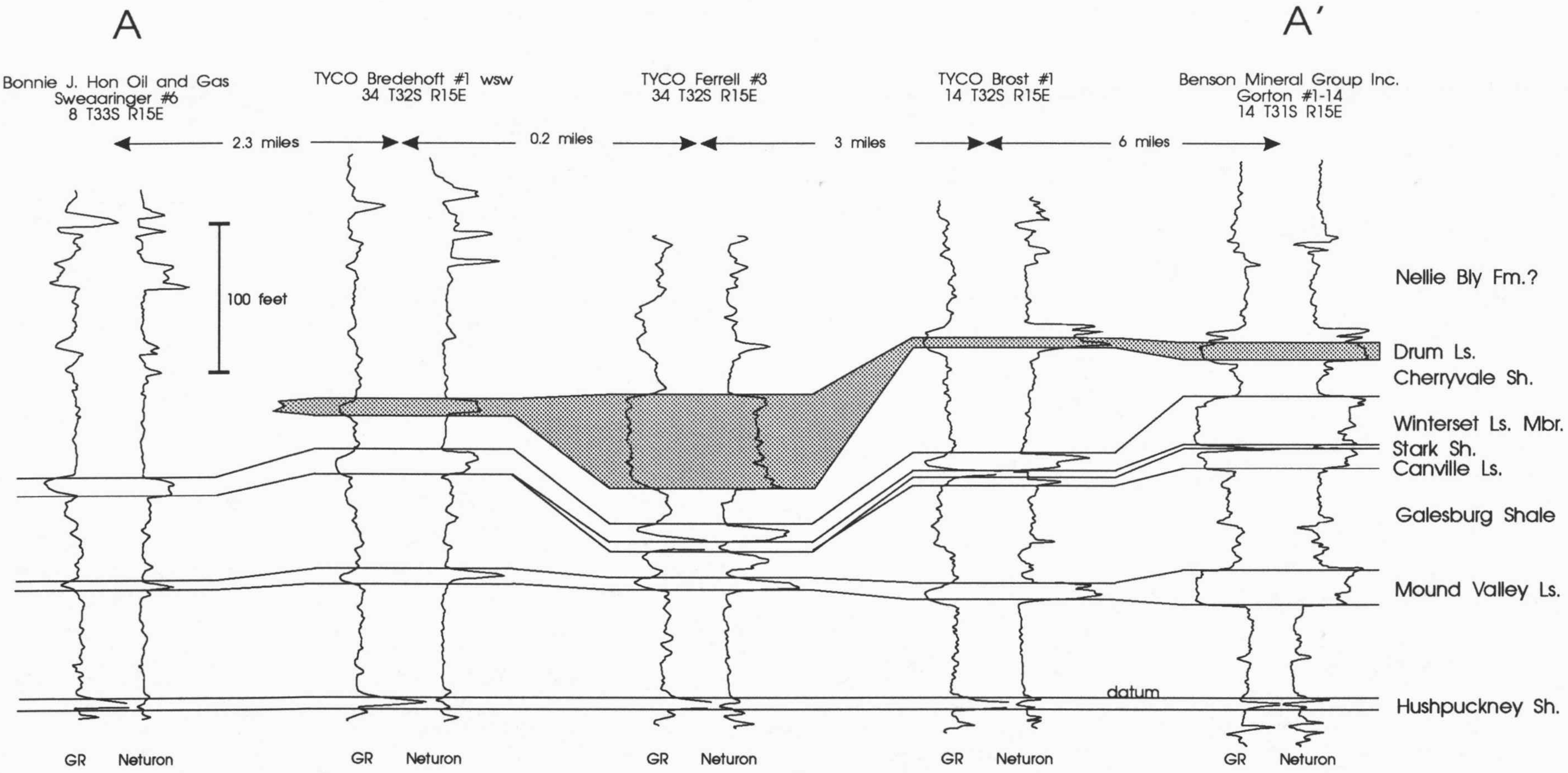


Figure 2.A.2.15. Isopach map of the Drum Limestone in a portion of the study area in central Montgomery County. Thicknesses are in feet.



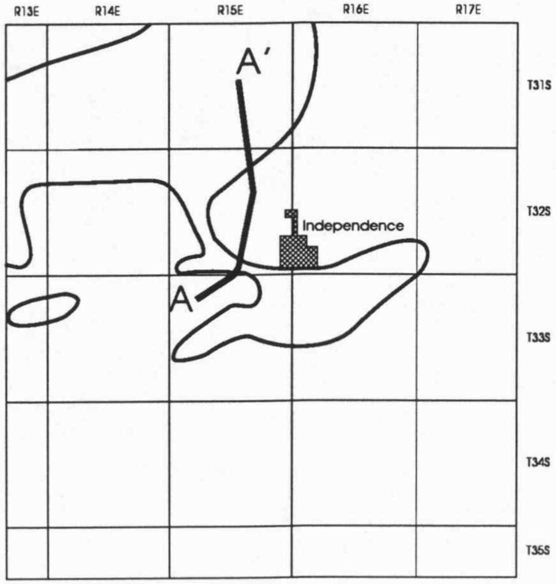


Figure 2.A.2.16. Cross section showing relationship between the Drum Limestone and related units. Note that the thickest Winterset Limestone, Cherryvale Shale, and Drum Limestone are in successively more southerly positions. Reference map of Montgomery County shows the 20 ft isopach line for the Drum Limestone.

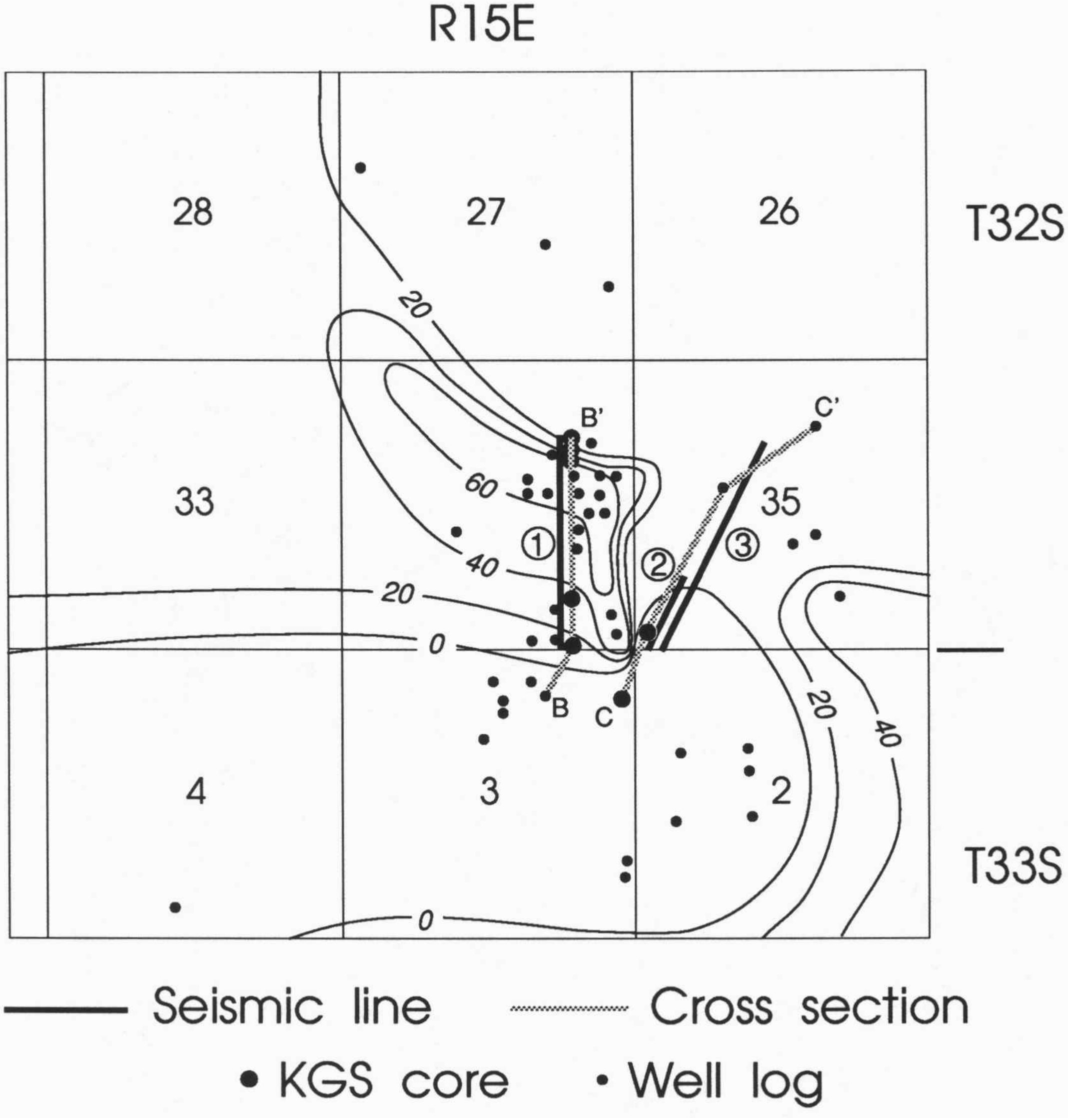


Figure 2.A.2.17. Map of seismic lines and adjacent coring transects. Circled numbers identify seismic lines referred to in text. Map is 3.2 miles wide.

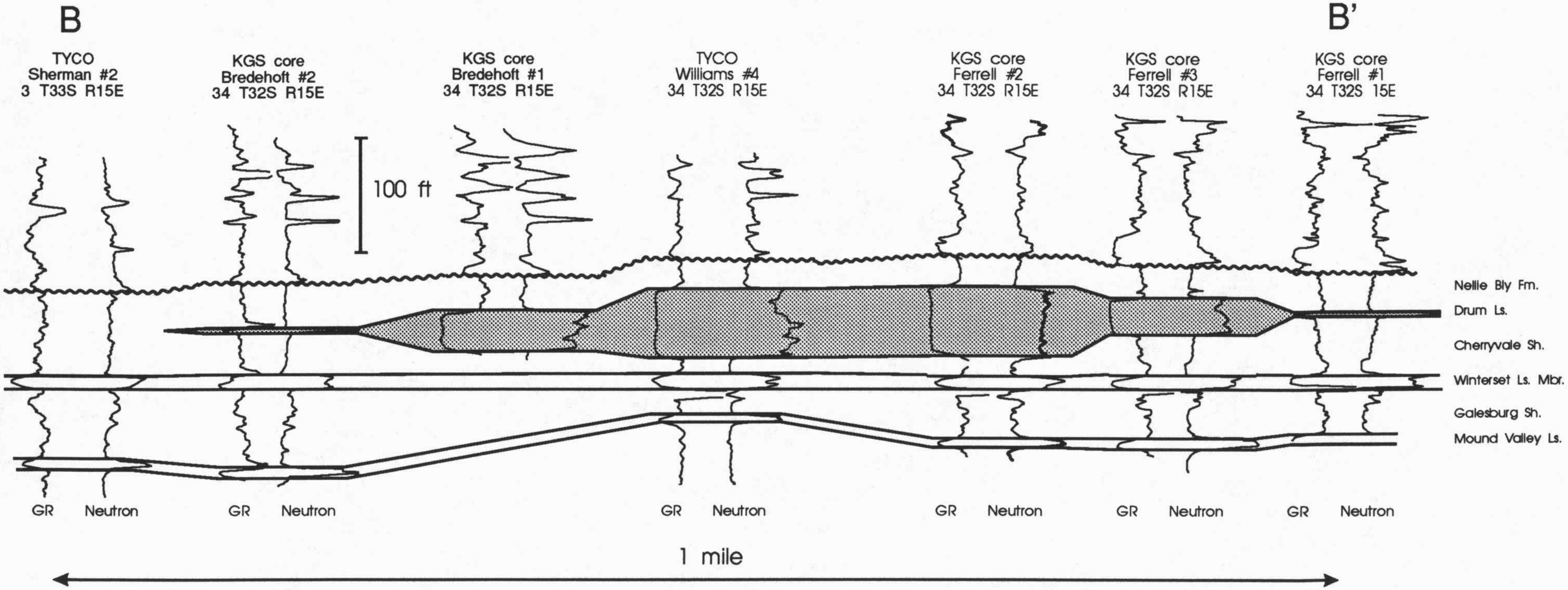


Figure 2.A.2.18. Cross section adjacent to seismic line 1. Refer to Fig. 2.A.2.17 for location of section.

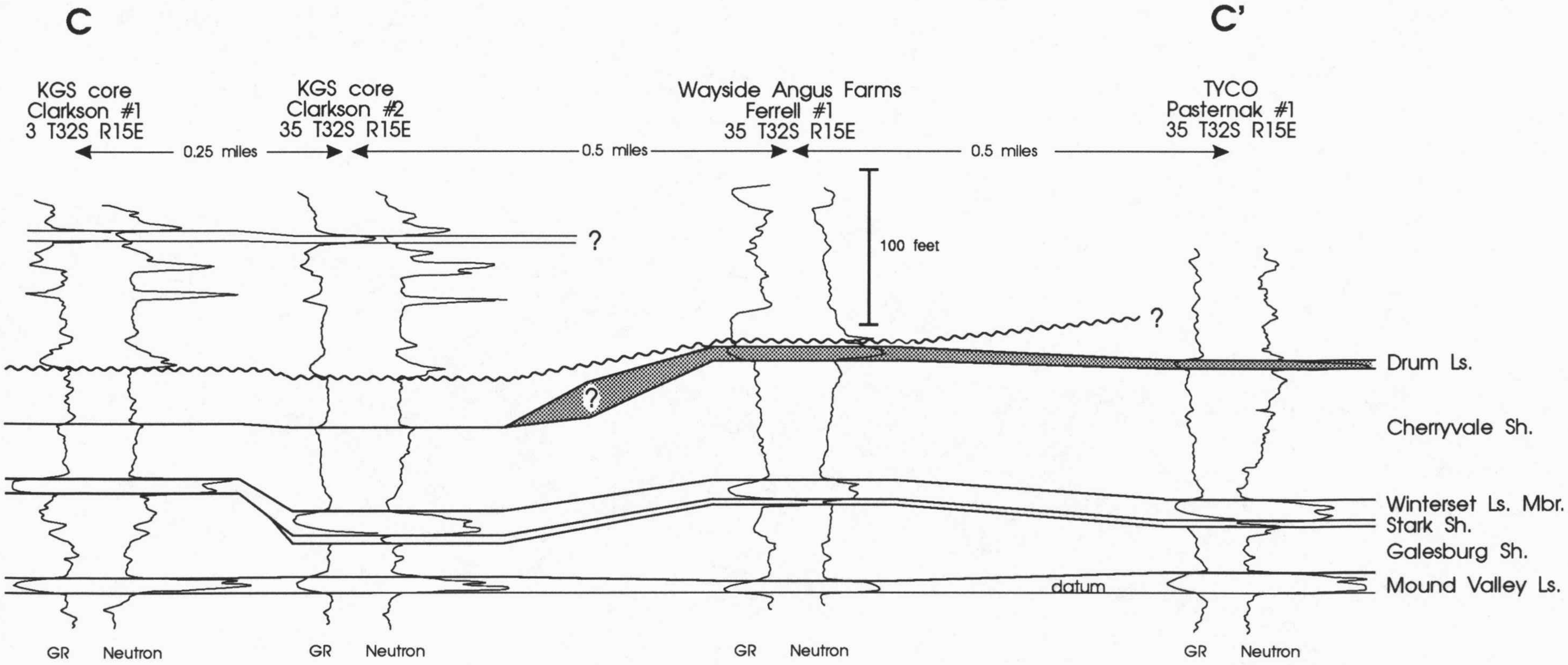


Figure 2.A.2.19. Cross section adjacent to seismic lines 2 and 3. The Drum Limestone oolite is aparently not developed in this location. Refer to Fig. 2.A.2.17 for location of section.

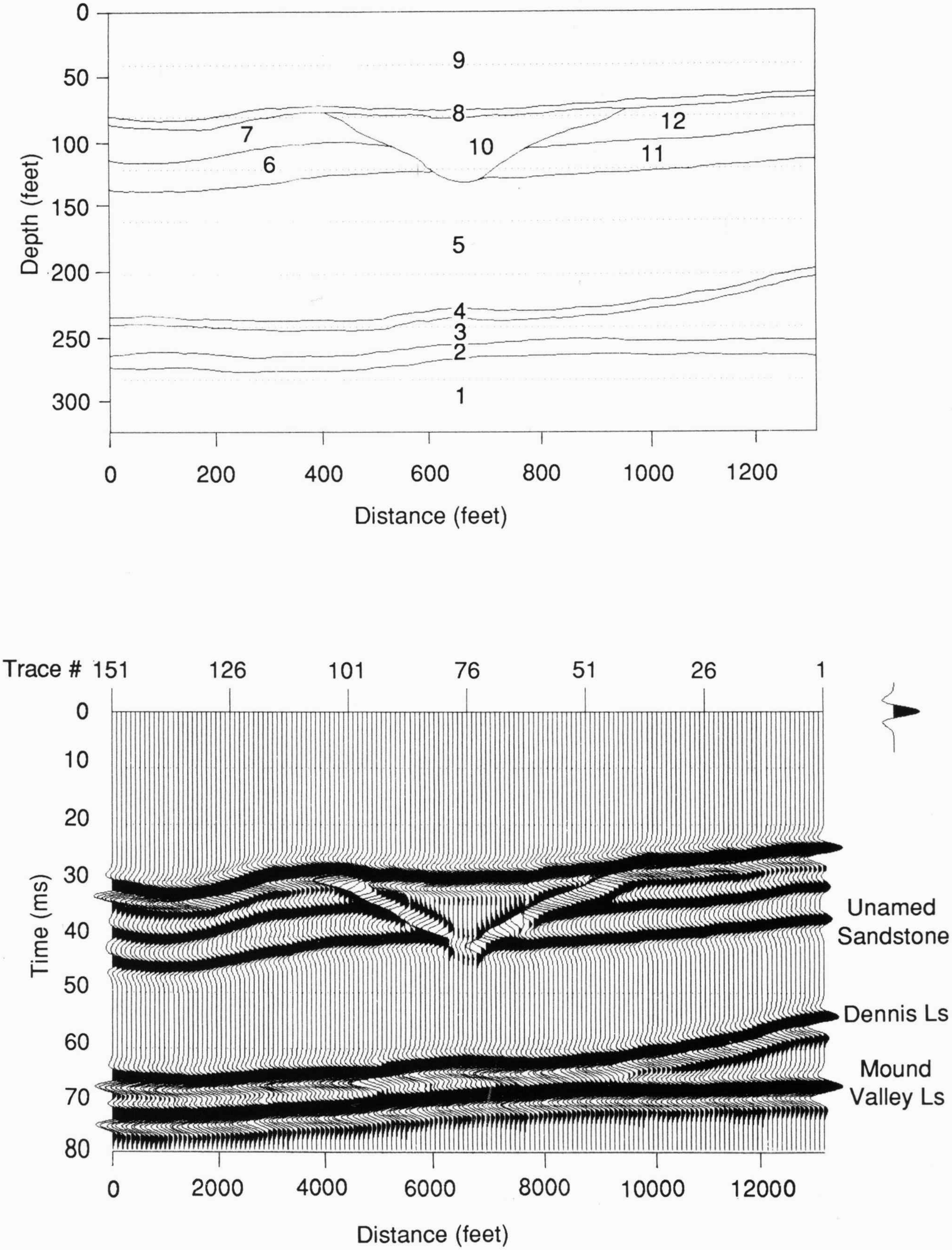


Figure 2.A.2.20. Geologic model (A) and synthetic seismogram (B) for line 2. Units of the geologic model are: 1, Ladore Shale; 2, Mound Valley Limestone; 3, Galesburg Shale; 4, Dennis Limestone; 5, Cherryvale Shale and Nellie Bly Formation; 6 and 11, unnamed sandstone; 7 and 12 shale, 8, shale; 10 shale-filled channel. Top of 8 is ground surface.

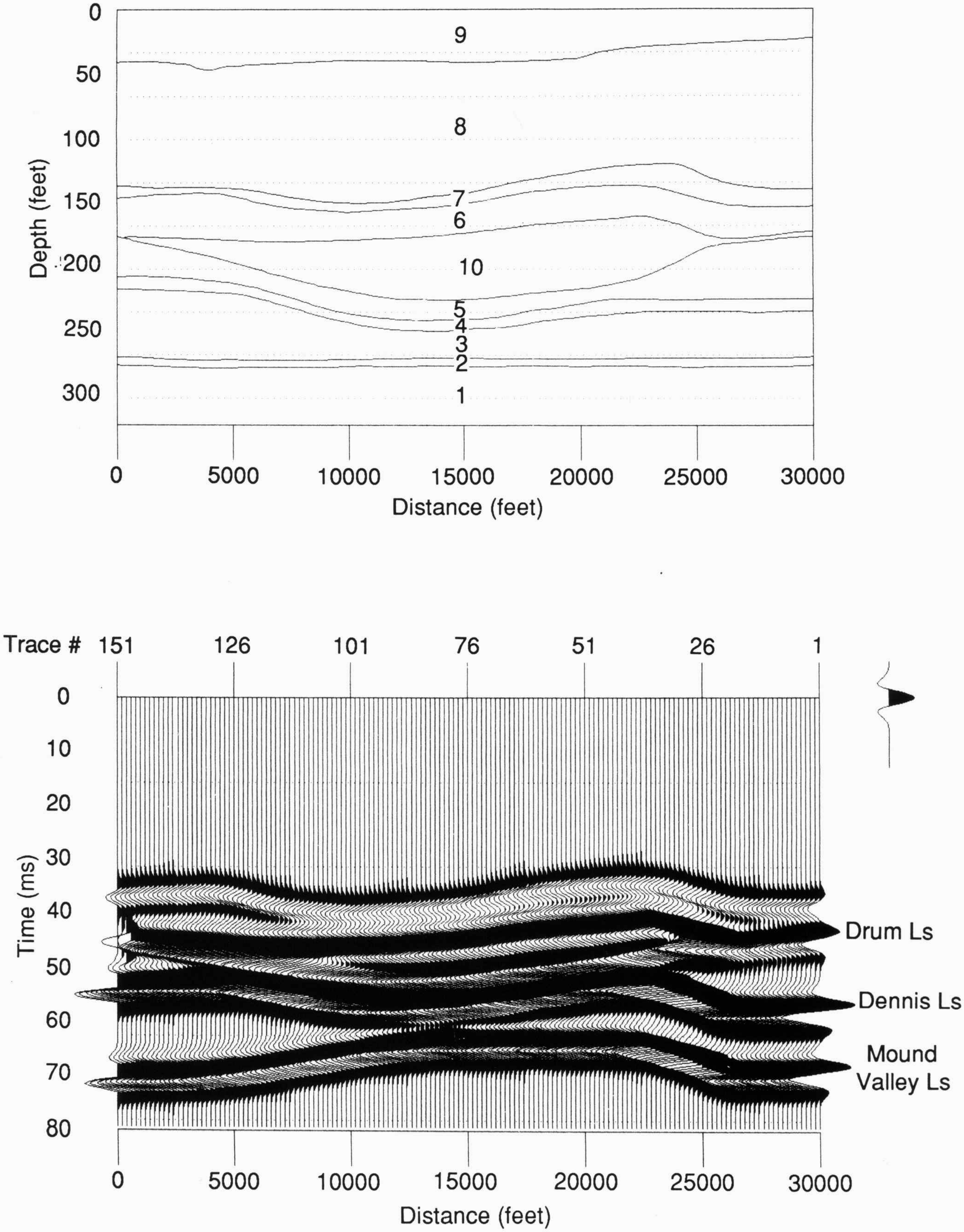


Figure 2.A.2.21. Geologic model (A) and synthetic seismogram (B) for line 1. Units of the geologic model are: 1, Ladore Shale; 2, Mound Valley Limestone; 3, Galesburg Shale; 4, Dennis Limestone; 5, Cherryvale Shale; 6, shale in Nellie Bly Formation; 7, unnamed sandstone; 8, shale; 10, Drum Limestone. Top of unit 8 is ground surface

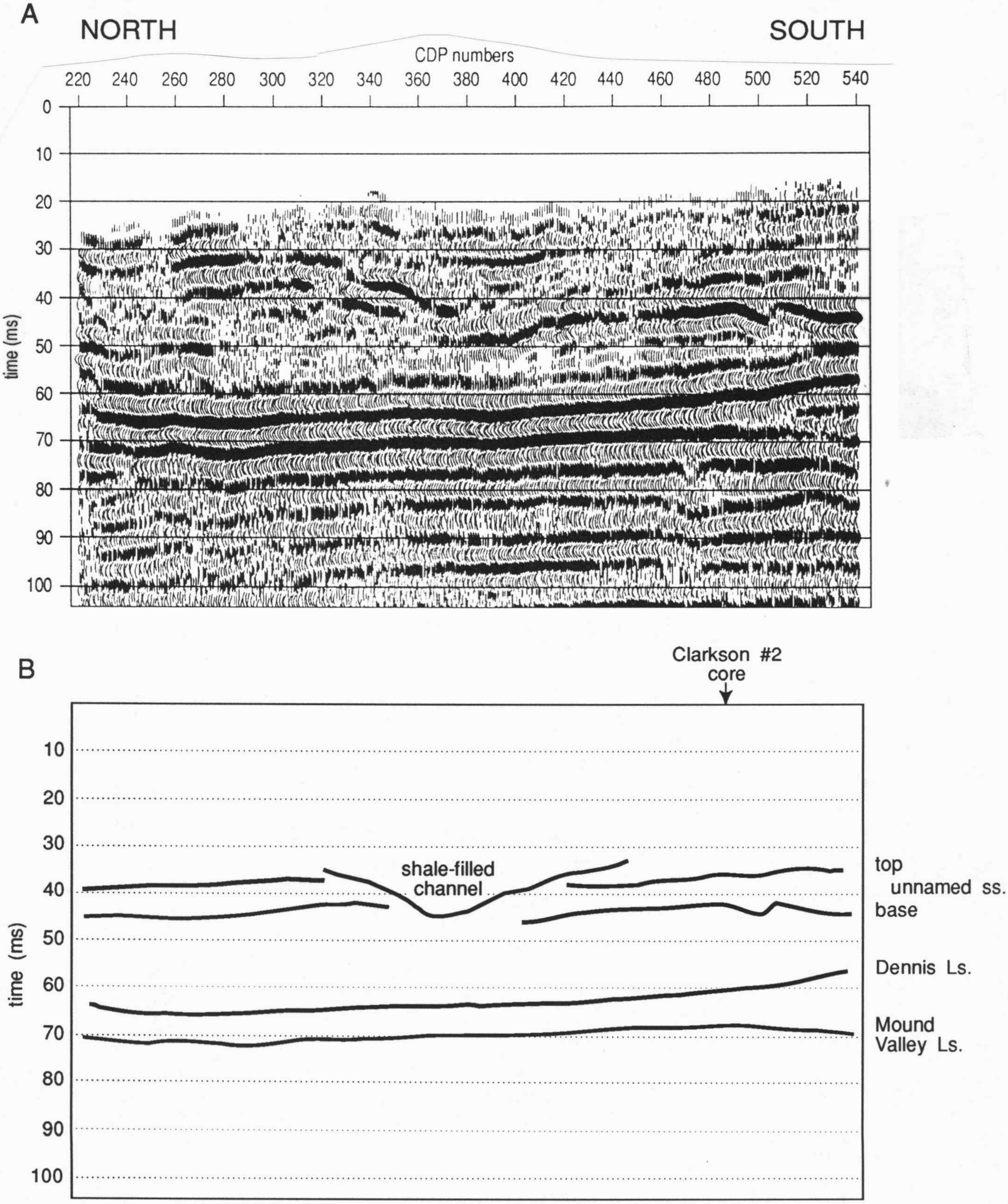


Figure 2.A.2.22. High resolution seismic line 2 (A) and interpretation (B). Length of seismic line is approximately 0.25 miles (0.4 km).

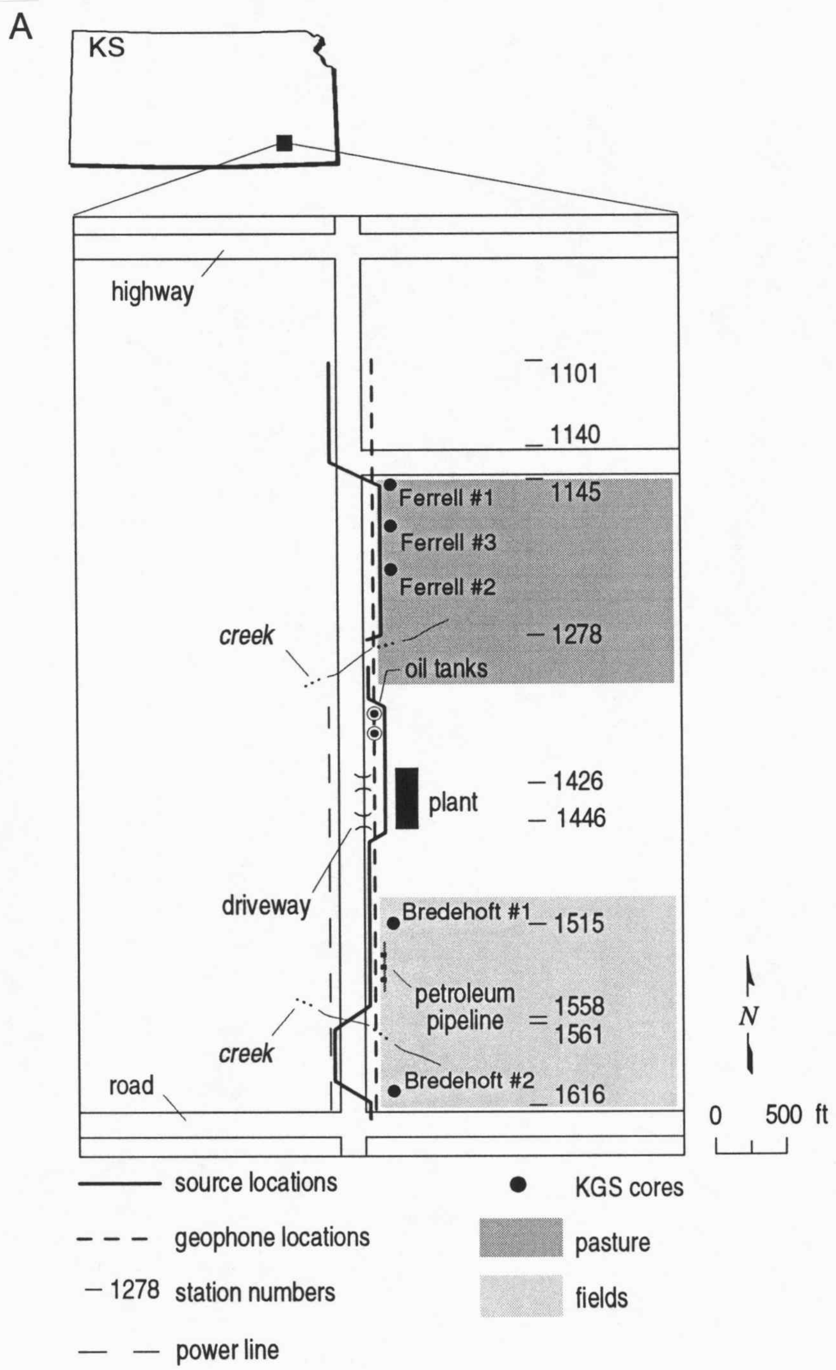


Figure 2.A.2.23. Seismogram of line 1. A. Location of seismic line showing location of KGS cores obtained along the transect. See also Figs. 2.A.2.17 and 2.A.2.18. B. Processed seismic line 1. C. Interpreted seismic line 1. B and C on next page.

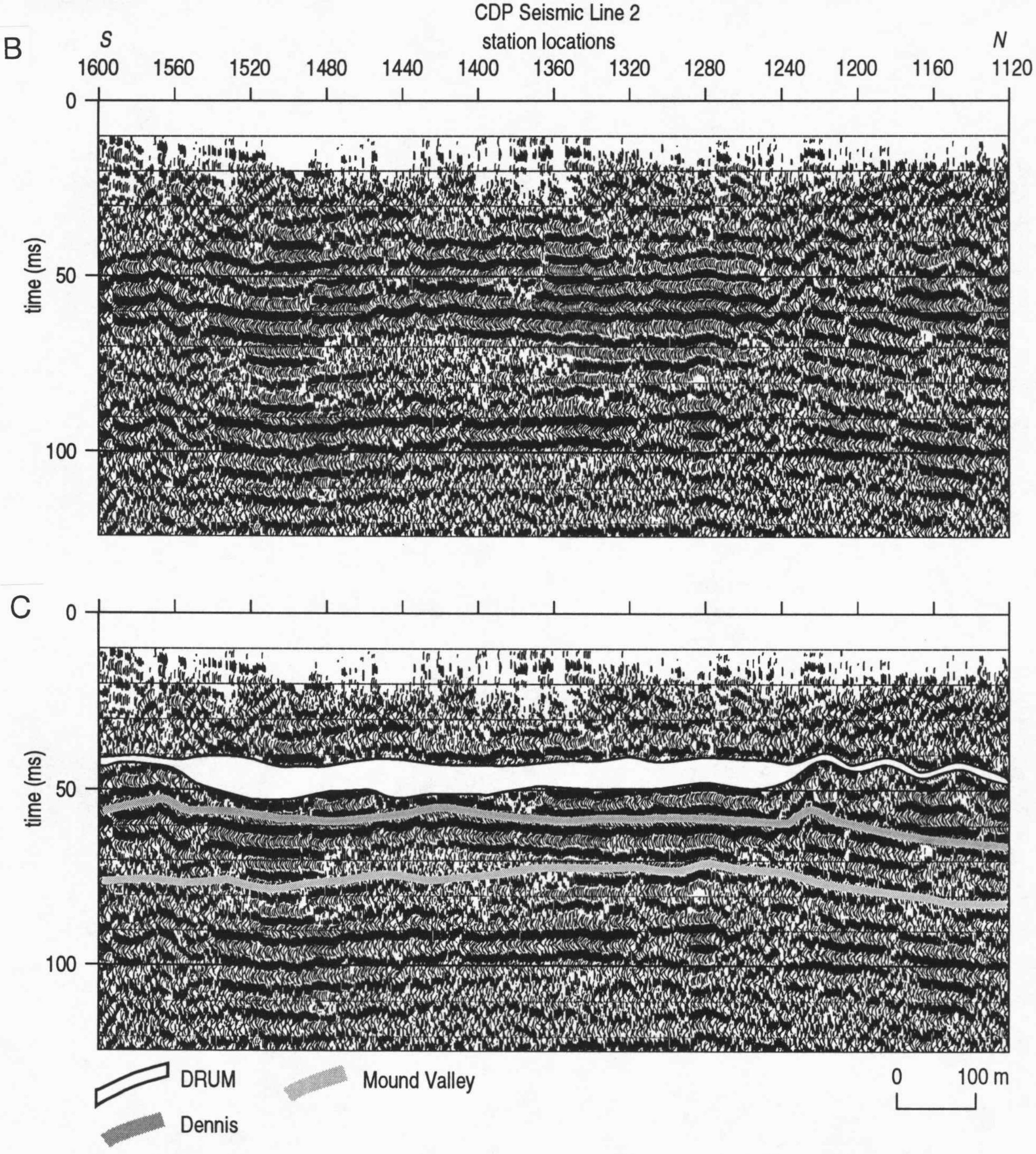


Figure 2.A.2.23. Continued.

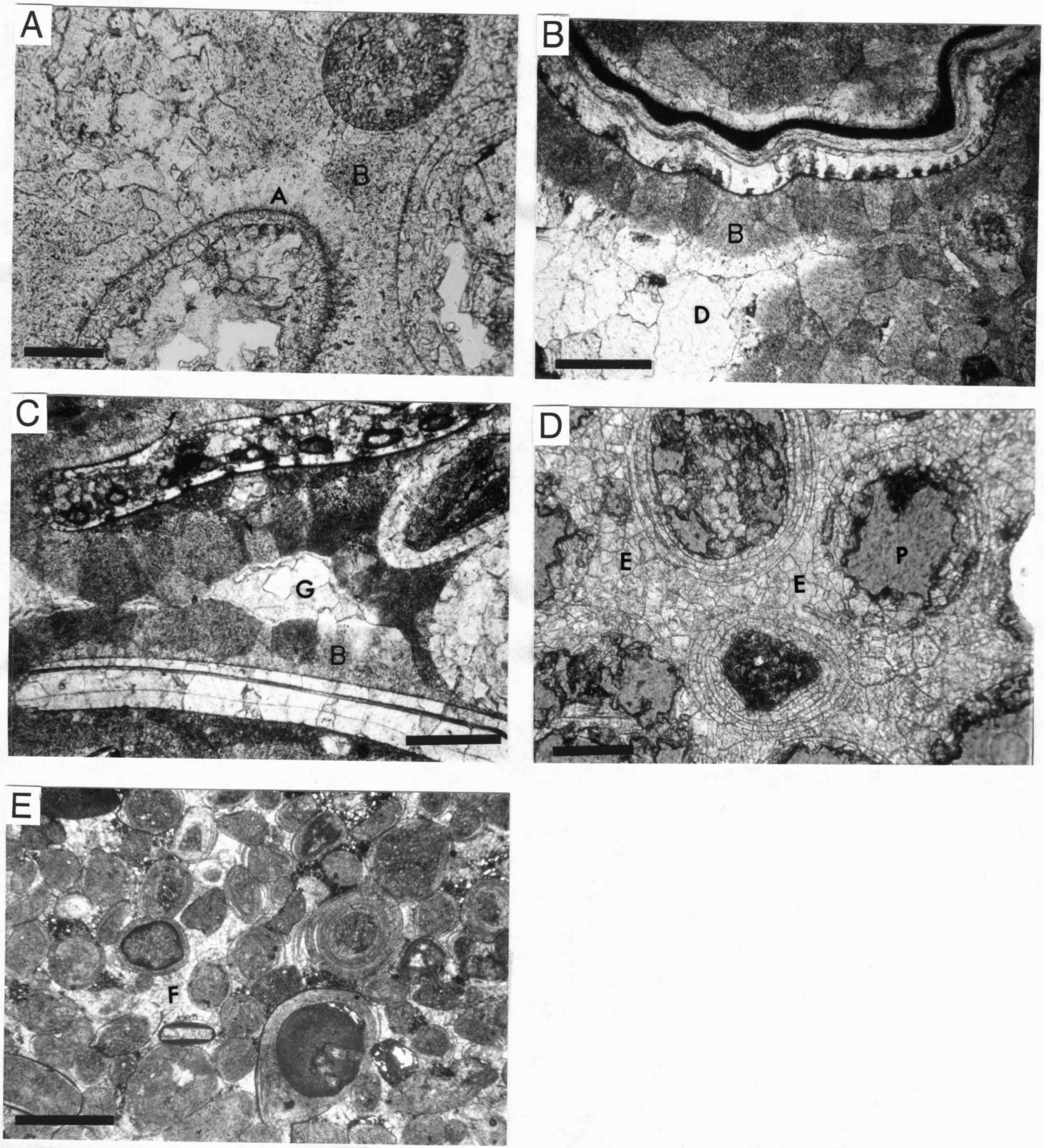


Figure 2.A.2.24. Cements in the Drum Limeston at the Heartland Cement Co. Quarry. A. The earliest cement is isopachous bladed calcite. Scale is 200 μm. B and C show isopachous, originally fibrous cement. Scales are 1 mm. D. Medium crystallin clear, equant calcite is the most common cement in the Drum Limestone oolite. Scale is 200 μm. E. Compacted grainstone from the uppermost Drum Limestone. All the cement is ferroan calcite. Scale is 1 mm. Cement key: A, isopachous bladed calcite; B, Isopachous cloudy, bladed to equant calcite; D, coarse crystalline, clear, equant calcite; E, medium crystalline, clear, equant calcite; F, coarse, equant, clear, ferroan calcite; G, baroque, ferroan dolomite. P, porosity.

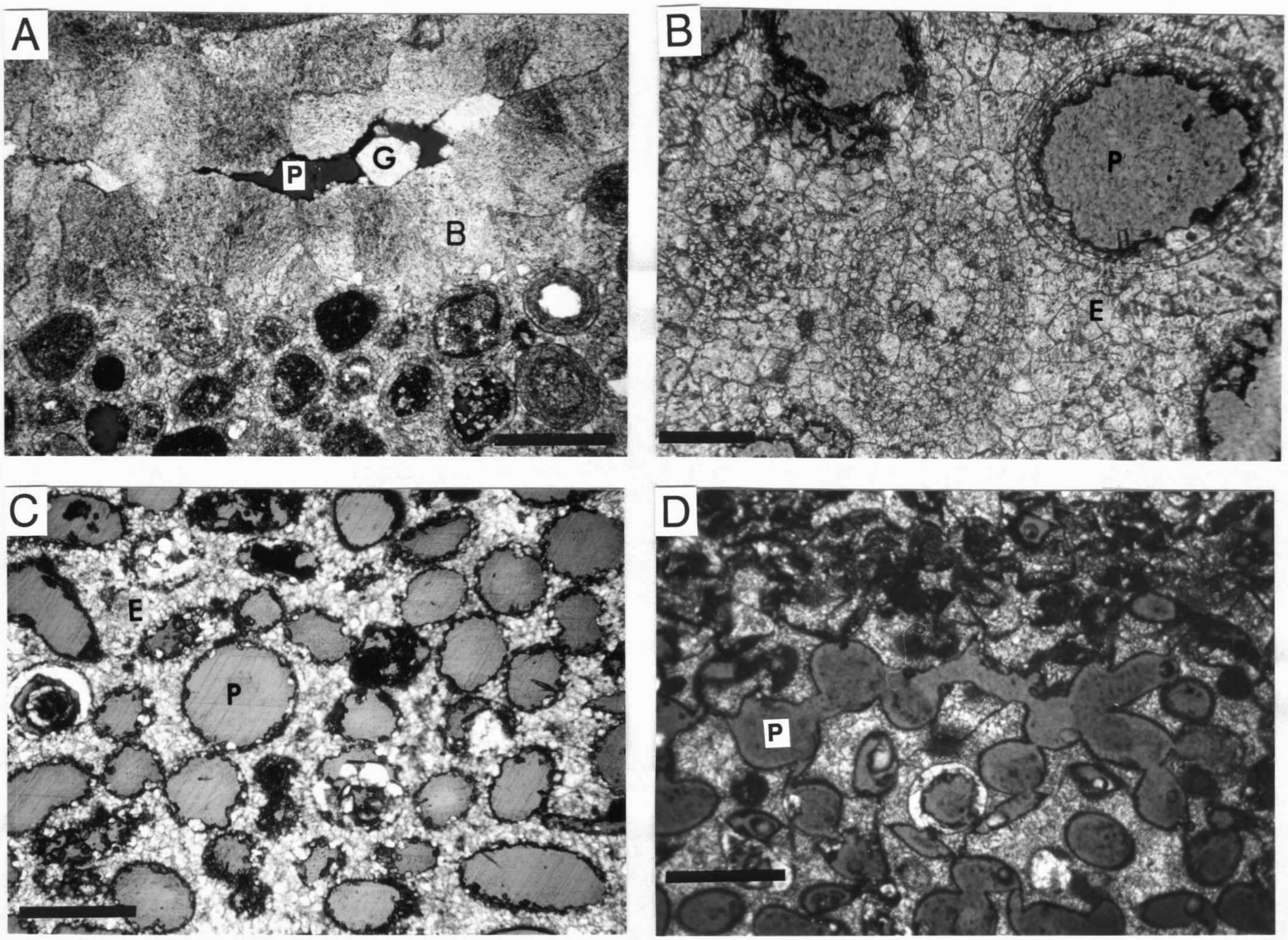


Figure 2.A.2.25. Porosity in the Drum Limestone at the Heartland Cement Co. Quarry. A. Primary porosity. Scale is 1 mm. B - D, secondary oomoldic porosity. B, isolated oomolds and highly altered ooids (center and middle left). Scale is 200 μm. C. Sample in which most ooids are dissolved, but few molds are connected. Scale is 1 mm. D. Partial crushing of oomolds dramatically increased permeability in lower portion of photomicrograph, and nearly complete crushing has reduced permeability in upper portion of photomicrograph. Scale is 1 mm. See Fig. 2.A.2.24 for key to cement types.

# APPENDIX A

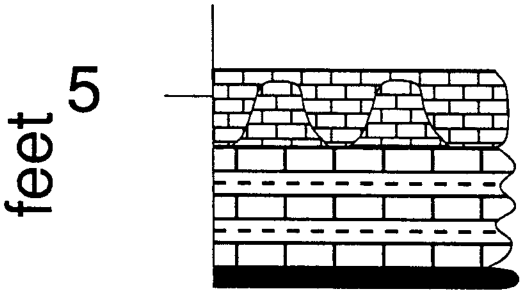
# OUTCROP DESCRIPTIONS

## Key to lithologic symbols
## (unless otherwise noted)

| | |
|---|---|
| ▦ | Skeletal oolitic grainstone |
| ▩ | Skeletal wackestone, packstone and boundstone |
| ▤ | Interbedded carbonate mudstone and shale |
| ■ | Skeletal intraclastic grainstone to packstone |
| ░ | Sandstone |
| ┅ | Shale |
| ☒ | Covered |

# CHE-1

s edge of sw sw s 9, T. 32 S, R. 17 E
Cherryvale Quadrangle
Montgomery County



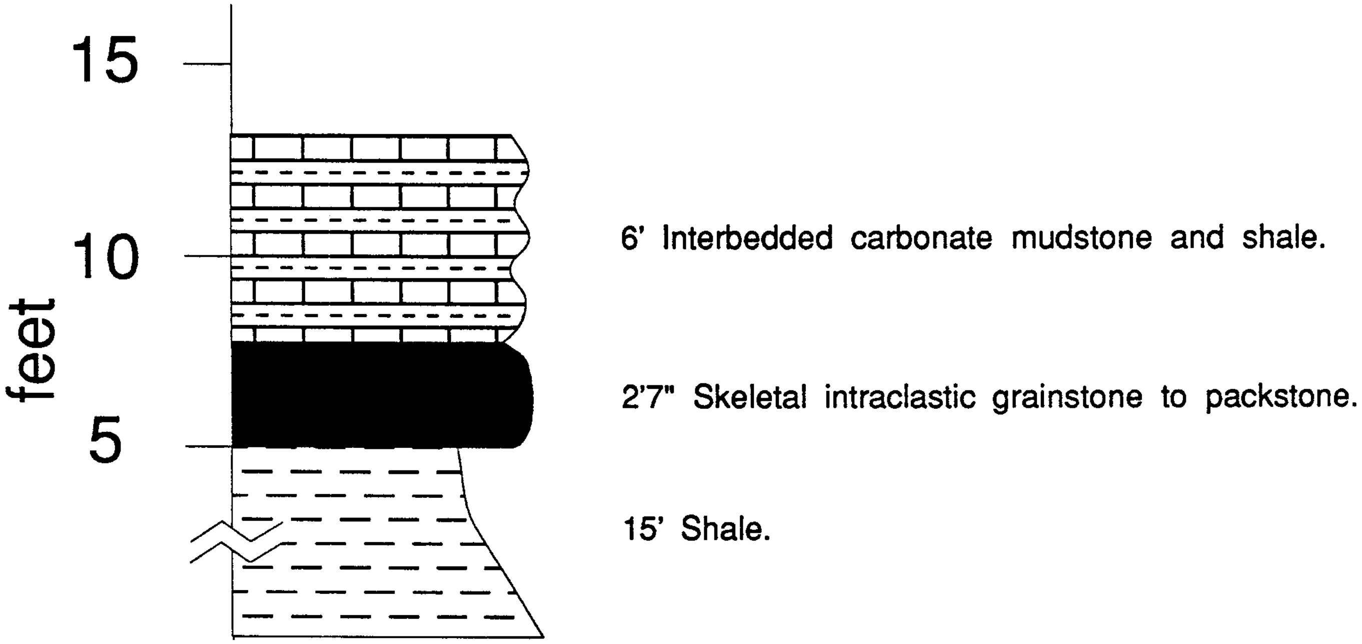
2' Stromatolitic limestone, fossiliferous wackestone to packstone between stromatolites.

3' Interbedded carbonate mudstone and shale.

2" Skeletal intraclastic grainstone to packstone.

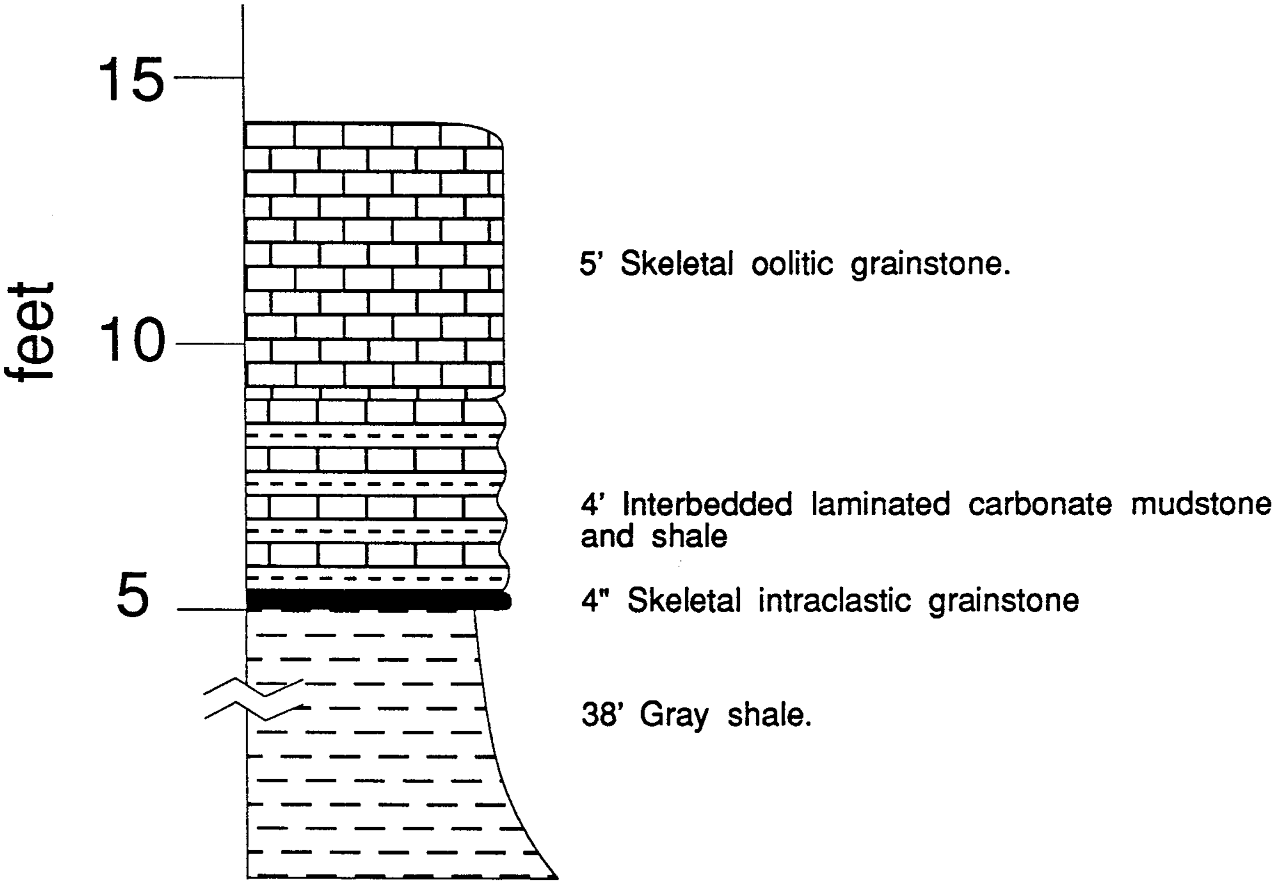
# LIB-2

sw sw sw s 25, T. 32 S, R. 16 E
Liberty Quadrangle
Montgomery County



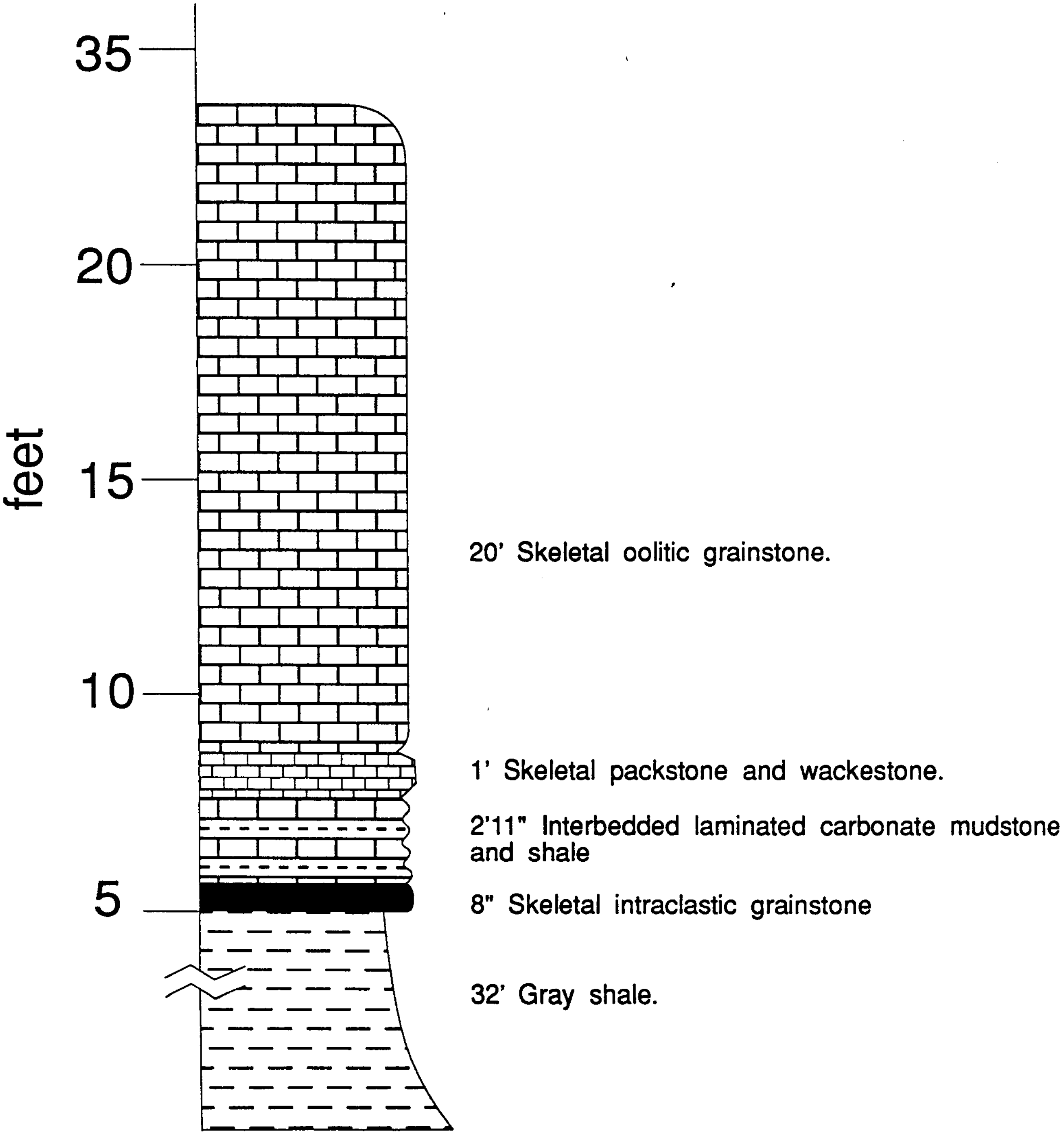
# LIB-3

1200 ft n of sw corner, s 31,T. 32 S, R. 17 E
Liberty Quadrangle
Montgomery County



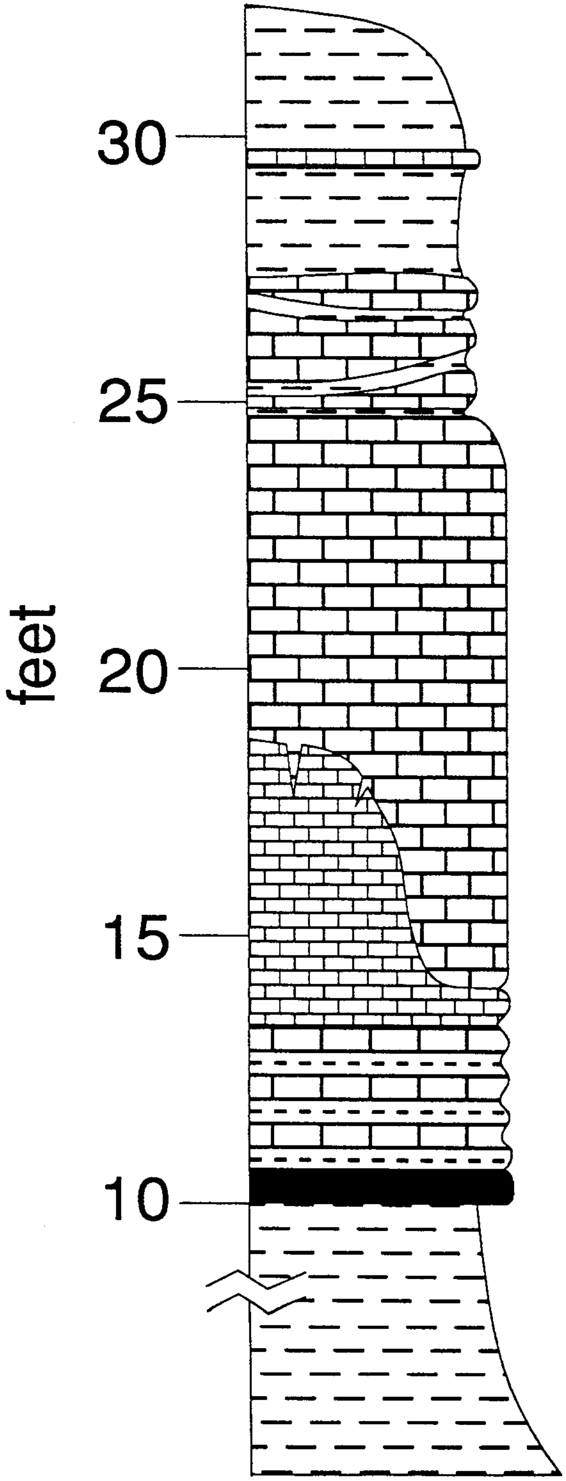
## LIB-4

s edge of sw s. 24, T. 32 S, R. 16 E
Liberty Quadrangle
Montgomery County



# LIB-5

s edge of sw sw s. 29 T. 32 S, R. 17 E
and s edge of sw s. 30 T. 32 S, R. 17 E
Liberty Quadrangle
Montgomery County



5' Silty shale with thin layers of fossiliferous packstone and cone-in-cone mudstone.

2'8" Interbedded skeletal oolitic grainstone and shale.

3'6" - 7' Skeletal oolitic grainstone.

5" - 5'5" Fossiliferous wackestone and boundstone. Laminated crust on upper surface.

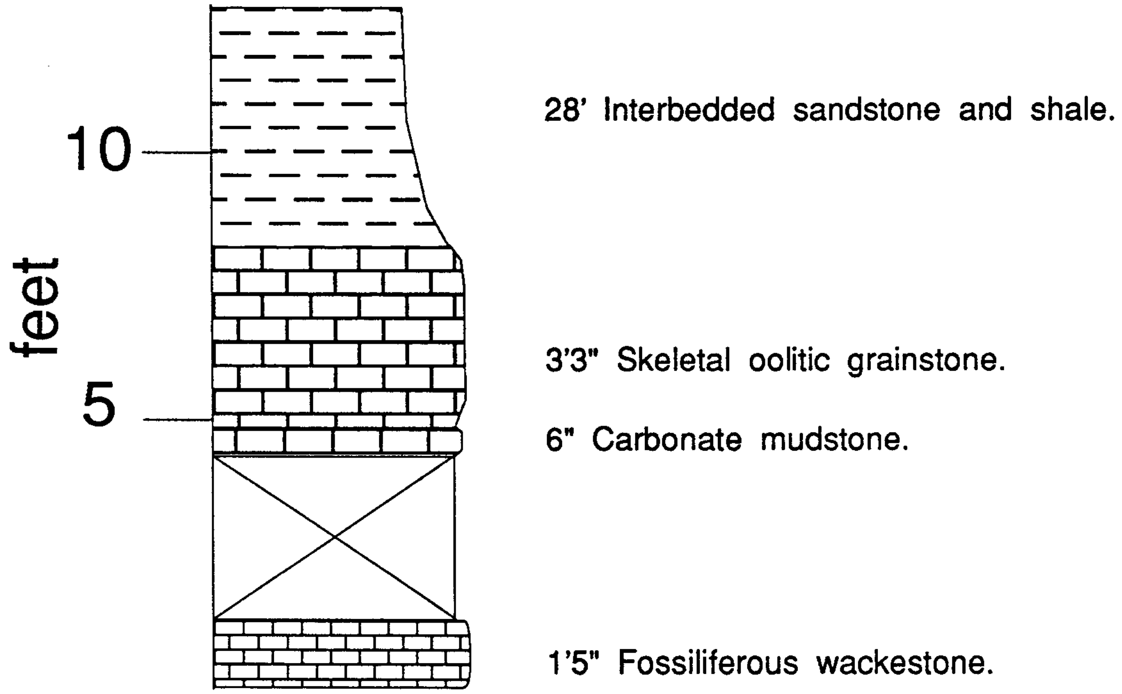
1'-2'7" Interbedded laminated carbonate mudstone and shale.

5-10" Skeletal intraclastic grainstone.

10' Gray shale.

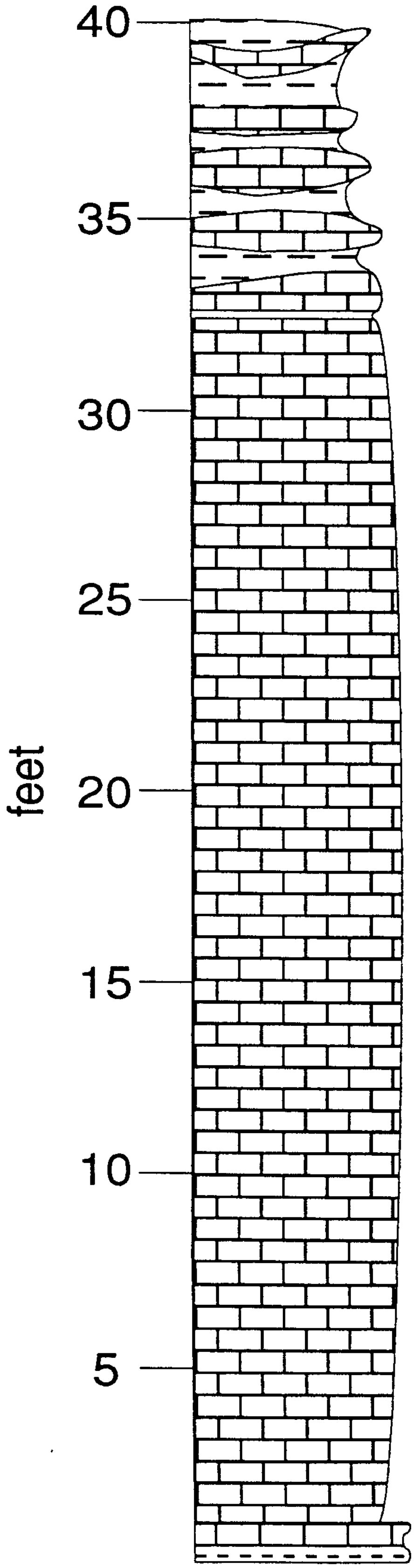
# SYC-2

nw nw ne s. 10, T. 32 S, R 15 E.
Sycamore Quadrangle
Montgomery County



# HEARTLAND CEMENT CO. QUARRY

S 1/2 s 5 and nw s 4 T. 32 S, R. 15 E
Independence Quadrangle
Montgomery County



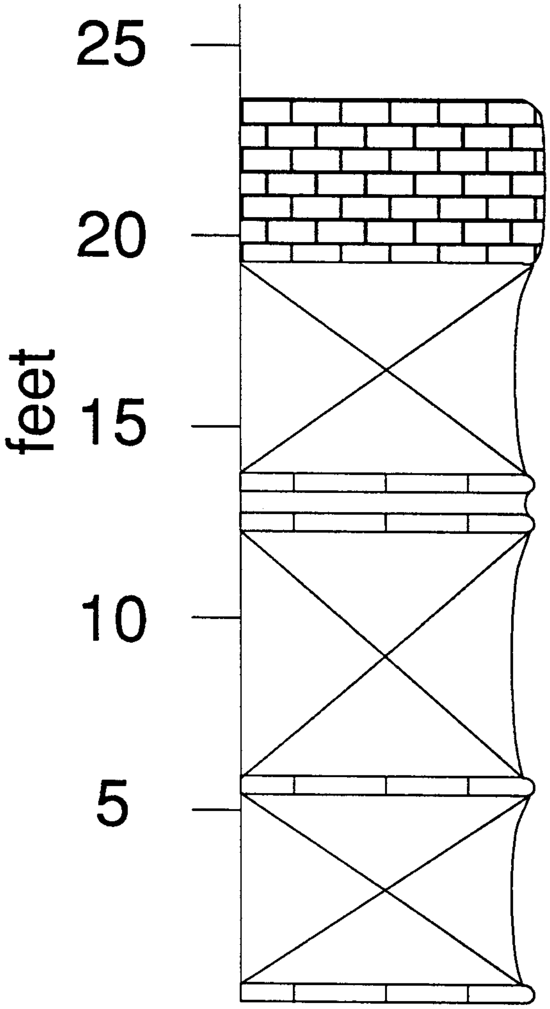
8' Interbedded skeletal oolitic grainstone and shale.

31' - 35' Skeletal oolitic grainstone.

1' Interbedded laminated carbonate mudstone and shale.

# IND-1

nw sw sw s. 35, T. 32 S, R. 15 E
Independence Quadrangle
Montgomery County

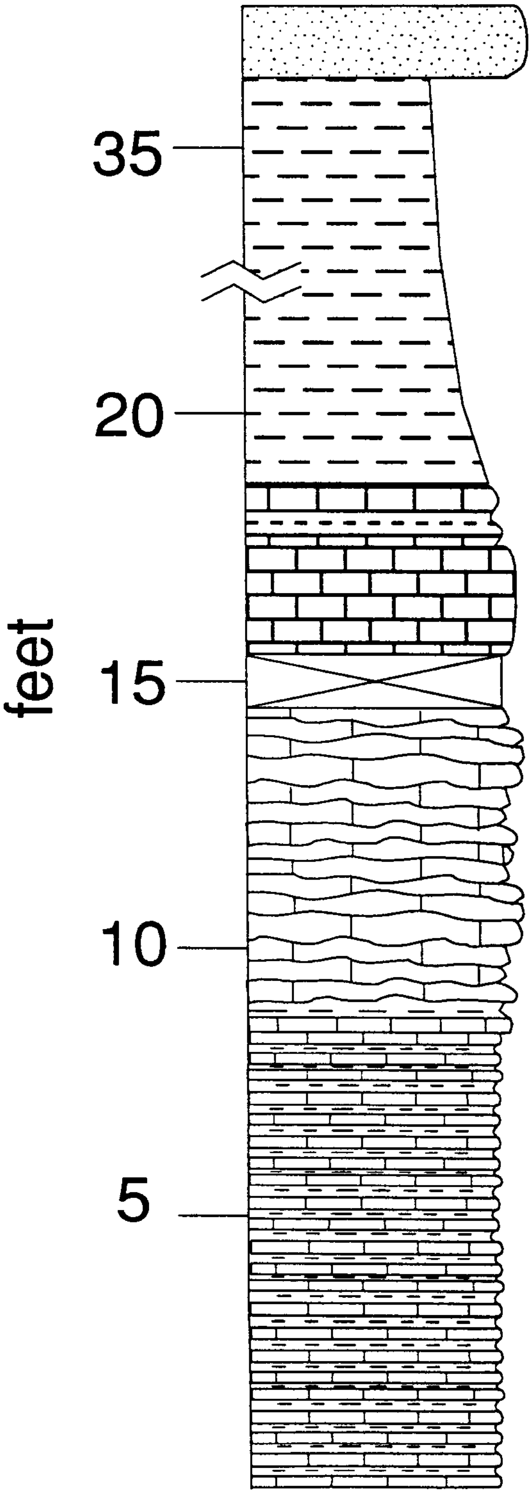


3' 7" Skeletal oolitic grainstone.

19' Mostly covered, isolated beds of micirite.

# IND-2

nw sw sw s. 28, T. 33 S, R. 16 E
Independence Quadrangle
Montgomery County



2' Micaceous sandstone.

17' Micaceous gray shale.

1'4" Interbedded shale and skeletal, oolitic grainstone. Shale interclasts.

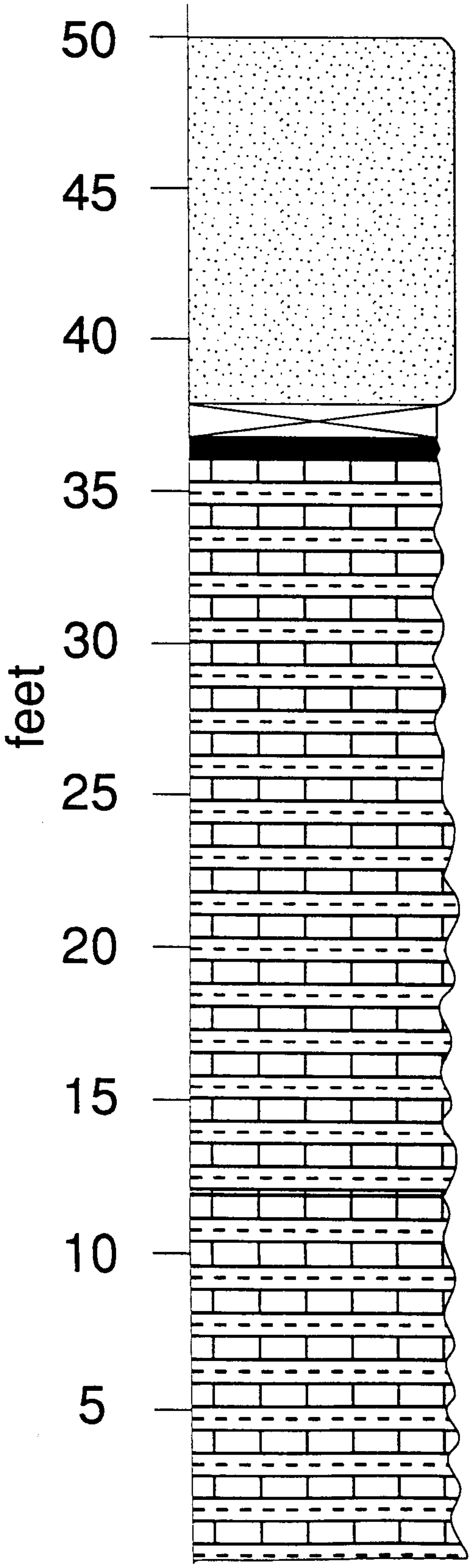
2 ' Oolitic grainstone.

9' Interbedded shale seams and bioturbated carbonate mudstone

6' Interbedded laminated carbonate mudstone and shale

# IND-4

sw sw nw s. 34 T. 33 S, R. 16 E
Independence Quadrangle
Montgomery County



12' Micaceous sandstone.

4" Intracalstic limestone.

24' Interbedded limestone (mudstone) and shale.

12' Interbedded limestone and shale
Limestone, skeletal grainstone to wackestone.

# IND-5

ne ne nw s. 33 T. 33 S, R. 16 E
Independence Quadrangle
Montgomery County